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PRACTICAL ALTERNATING CURRENTS

NEWTON HARRISON

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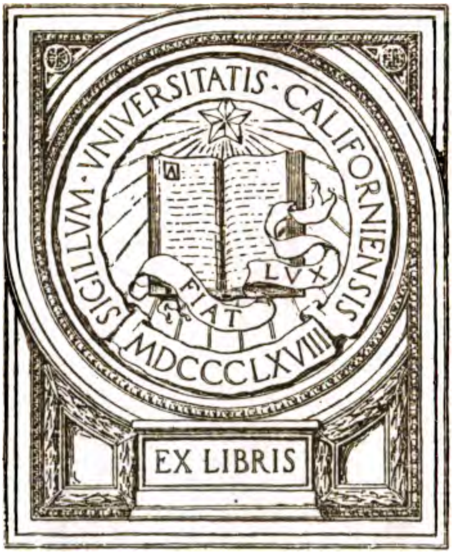

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PRACTICAL ALTERNATING CURRENTS
AND POWER TRANSMISSION

Practical Alternating Currents and Power Transmission

BY

NEWTON HARRISON, E.E.

Instructor of Electrical Engineering in the Newark Technical School
Author of "Electric-Wiring, Diagrams and Switchboards"

A PRACTICAL TREATISE ON THE PRINCIPLES AND APPLICATIONS OF ALTERNATING CURRENTS TO CENTRAL STATION AND POWER-HOUSE PLANTS, INCLUDING THE ELEMENTS OF POWER TRANSMISSION. ENRICHED BY ONE HUNDRED AND SEVENTY-TWO ILLUSTRATIONS

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PREFACE

THE correct treatment of a subject like alternating currents has been regarded, with much truth, as being consistently mathematical on all occasions. The fact of the matter is, that however mathematical the treatment of the theory may seem to be, the practice is within the scope of any earnest reader's intelligence. In other words, opinions are apt to differ as to what is the correct treatment of a subject. To the student of academic forms, mathematics in this case would be the only reason for the treatment being given any consideration at all. To the practical man, interested in the most explicit and, to him, the least mathematical presentation possible, academic forms are looked upon askance. In consequence, the line of division is strongly drawn between the reading matter palatable to the mental taste of one and the other. Calculus is naturally a useful and time-saving tool in making an analysis, but how many regard it as a readily comprehended form of expression in connection with ordinary phraseology and practical, everyday work? There must be, instead of this, a departure if possible, one which is made only to suit those for whom such a departure is absolutely essential under the circumstances. Therefore this little volume, entitled "Practical Alternating Currents," was prepared in the belief that it represented what was wanted and what would

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prove comprehensible and useful. There is, and will always continue to be, much more to a subject than a volume on it will cover; but then the purpose of the volume must be considered. It is here that light is best thrown upon the situation and misunderstanding avoided.

A book must stand upon its own merits, with its purpose evident to the reader's eye. Such a one as this has the purpose in view of discussing alternating currents in as unmathematical a form as possible. It is intended to cover practical conditions with reference to the principles upon which they rest, with arithmetic as the basis of all such calculations, comparisons, and results found therein. The subject has been entered into from a power-transmission-and-distribution standpoint. For this reason, some of the preliminary matter found in other books has been left out. Yet the author believes that enough ground has been covered to give a good working knowledge to the reader without such a preamble.

As far as possible the practice has been given first place, and all the author can honestly claim is a manner of explanation that, it is hoped, will prove to some an easier means of reaching the truth than has been their experience heretofore.

It must be understood, however, before this Preface is closed, that a non-producing class exist, whose main work consists in the assumption of superior attitudes toward the earnest efforts of others, particularly when crystallized in book form. They are found in the field of science, as everywhere else, and have their say. It may be unnecessary to state that this volume is not intended for them, though in all likelihood it will not escape their attention.

If, instead of this class, the pages of this book are read with care by those for whom it is intended—the real workers—the author expects but one response. Imperfections are found in the productions of all hands, skilled or unskilled, and for that reason they will be found here as well, in all probability. The imperfections, however, are not the things to be judged, but the bulk of the subject-matter as it stands. On this basis the author is prepared to offer his work to those constituting themselves his readers, with complete contentment, for the outlines of the book are based upon natural law, and this has always seemed to him sufficiently stable to authoritatively support a treatise devoted to useful purposes.

NEWTON HARRISON.

September, 1906.

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CHAPTER I

INTRODUCTION.—CONDITIONS OF ELECTRIC LIGHTING.—CHARACTER OF CURRENT EMPLOYED.—COMPARISON OF CIRCUITS FOR EQUAL POWER.—PRESSURES OF STANDARD GENERATORS.—CAPACITY OF MACHINES.—SELECTION OF LAMPS.—RETURNS FROM GENERATORS.—COST OF HIGH EFFICIENCY.—ELEMENTS OF POWER.—CONTINUOUS CURRENT CALCULATIONS.—SOURCES OF POWER.—POWER FROM WAVES.

Introduction.—The field of engineering has broadened sufficiently to include more than the term itself implies. Engineering, as now construed, is not limited entirely to the consideration of those problems hitherto regarded as belonging entirely to its peculiar domain. On the contrary, it embraces the most important problems of the hour, as far as material comforts are concerned. It enters into the field of illumination, with the purpose of pointing out, as well as crystallizing, the principles upon which that which is called illumination and wiring are based. It enters into the field of heating and cooking, regarding these domestic propositions as part of the scheme as now outlined. Hygienically, it not only offers to be the means by which sight is preserved by the development of a bright and uniform light in all homes and public places, but it offers to supply, by the use of electricity, means by which the temperature of buildings, whatever their purpose may be, is sustained without the use of steam or heated air. As a source of light, electricity is a non-oxygen-consuming form of illumination, and as such is justifiably the superior of any other source of light suggested or utilized. As a source of heat it withdraws nothing from the surrounding atmosphere, leaving it as before with its full quota of oxygen gas. In these two respects the applications of electricity have such pronounced advantages that the only situation left to consider is that relating to the cost of production in either case. In that of light, the public estimation of its value for street and private lighting leaves little to be said. As regards its use for heating, the question of cost appears as the only element requiring a better solution. Although generally regarded as the only and ultimate means of light and heat in the future, electricity is not entirely within the scope of the general public as an ordinary commodity. When its introduction begins in the average home, then lighting will fill its expected niche in the category of household wants. Both light and heat as produced by electricity represent distinct departments of electrical engineering, requiring separate treatment and consideration. They, in common with power produced by the same means, are broad enough in their scope to cover a field of such great dimensions that, with the exception of the principles and methods employed in the transmission of intelligence, or isolated instances of the application of electricity in medical treatment or research, electrical engineering as thus defined enters into the operation of city and suburban life more than any other force to which reference could be made.

Conditions of Electric Lighting.—Without a demand for an electric-light equipment no community can feel justified in encouraging the erection of such a plant. The conditions of electric lighting are those which primarily arise through the necessity for a better form of illumination, more than through the fact that either a power or fuel source is conveniently near, or an enterprise of some sort is required to give that touch to town or city life best secured through the use of electricity for lighting. Yet whether these circumstances appear or not, the conditions of electric lighting are those which enter into a consideration of the following:

1. Whether the community to be supplied with a plant is compact and represented by stores and private dwellings, as well as needing light in its principal thoroughfares.

2. Whether the community to be supplied with a plant is of a scattered nature, though represented by stores and private dwellings, as well as needing light in its principal thoroughfares.

3. Whether the character of the community is sufficiently permanent to lead to the conclusion that further extensions of the system will be imperative to meet the demand for light.

4. Whether the growth of the community is suffi-

ciently independent of large factories to possess the inherent power of expansion without regard to the success of said factories.

5. Whether the community is large enough in size to require more than one center of distribution in the lighting scheme, such as sub-stations, etc.

6. Whether a single station will be sufficient to supply all requirements when the expected contracts for light are closed with the municipality and the private consumers desiring electricity.

7. Whether water-power or coal will be utilized for the purpose of operating the plant, or both; in which case the temperature variations during the year will have to be taken into account to determine during what part of the year the water will be serviceable as a source of power.

8. Whether a contract can be closed with the village, town, or city, for public lighting, to partly guarantee the success of the project.

9. Whether the transportation of machinery is within the scope of the facilities afforded, or whether heavy additional expense for machinery would have to be added through inadequate railroad connections.

10. Whether skilled help can be secured with ease, or with that difficulty which would add unduly to the running expenses of the plant.

Along these lines the conditions of electric lighting may receive the attention necessary to secure an intelligent appreciation of all requirements. Other items, in addition to those enumerated, may be added, as fresh circumstances arise, when the final consideration of essential details will bring them to view. But although it is customary to regard this particular department of applied electricity as a purely technical proposition, it is clearly evident that as a technical business proposition it emphatically holds first place. Instances of where gas-lighting plants were installed long before the electric-light plant, have given rise to the question whether such competition, when keen, can lead to any form of success in a contracted community.

In other words, the best conditions for the healthy development of the electric-light industry are those which first mean a popular demand for illumination of this character; second, the possibility of expansion on the part of the town; and, third, a price for water-power or fuel which permits a reasonable profit in its transformation from mechanical to electrical energy.

Character of the Current Employed.—The expense of installing an electric-light plant is only a part of the total expense invited by the enterprise. The erection of pole-lines or the interment of the conductors underground is well recognized as a feature of the construction which is as necessary as it is subsequently costly to keep in repair. In this respect the setting of the poles, the choice of the insulators, and the size of the copper conductors are bound to have a future effect upon the operation of the plant.

On the other hand, the town may be several miles in length (Fig. 1), with its business center, important streets or avenues, and suburban homes stretching along over a considerable distance. A long pole-line would thus become a necessity for the distribution of the current to the various points of tap. If the town is grouped around a given center, with the population comparatively thick in numbers and then thinning rapidly (Fig. 2), the problem of choosing current becomes much simplified. The currents to be generated belong to either of two kinds, as follows:

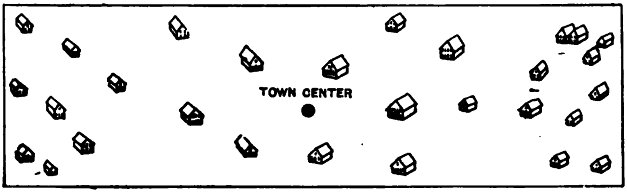


FIG. 1.—A Town with Lighting Greatly Distributed.

First—Alternating current of high pressure, used in conjunction with transformers for converting it to a lower pressure whenever necessary.

Second—Direct or continuous current of comparatively low pressure, for use just as generated in stores, streets, or homes along the line, or within easy access of it.

The use of alternating and direct current in small communities is governed by the geographical position of them, as already stated. The cost of an alternating- and direct-current plant for equal amounts of lighting displays this feature: That under propitious circumstances it is better to use direct than single-phase alternating current, for the reason that motors cannot be readily run by the latter except when specially constructed. Whereas the direct is in some respects an advantage, it is also a more expensive form of energy to conduct; because, if transmitted at a high pressure, it is not readily transformed down, and for equal powers in comparison with the alternating current, takes very much more copper.

But the proposition which practice has laid down is this, that when the towns are distributed over a large area, the alternating is by far the best current to employ. On the other hand, if a particular case presents itself, of a village or town closely grouped, then the cost of a direct-current plant, with its convenience, would become readily apparent, if the use of power for small motors is considered. The conclusions reached are, therefore, as follows:

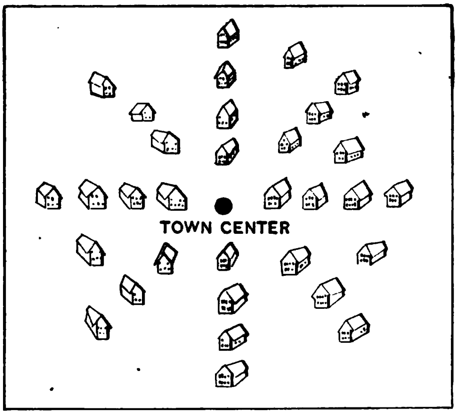


FIG. 2.—A Town with Lighting Concentrated.

First—A straggling town covering considerable area and distance is a case where alternating current is the only form of electricity to employ.

Second—A small, compactly settled town is a case where the use of direct current is worthy of first consideration.

Comparison of the Circuits for Equal Power.—The only means of comparing the sizes of copper wire required in the case of a given amount of electrical energy transmitted, as high-pressure alternating or low-pressure direct, is by estimating the relative cross-sections of copper required for equal lengths of circuit. Taking a given case of 100 kilowatts of power, transmitted as alternating current a distance of one-half mile, at a pressure of 2,000 volts, the total watts would equal 100 × 1,000 = 100,000. At 2,000 volts pressure the amperes would be equal to 100,000 ÷ 2,000 = 50, without paying any attention to the losses experienced through inductive efforts, etc. At present the size of wire required with a single-phase system would be, with an allowance of 10 per cent. drop in the line, not much less than

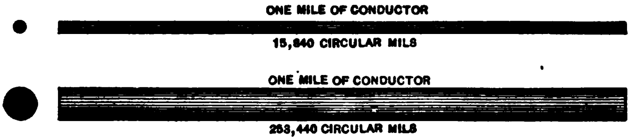


FIG. 3.—Comparison of the Two Sizes of Conductors Carrying Equal Power.

$$\text{C. M.} = \frac{\text{Length of line in ft.} \times \text{amperes} \times 12}{\text{volts drop}}$$

$$= \frac{5{,}280 \times 50 \times 12}{200} = 15{,}840 \text{ cir. mils,}$$

or about a No. 8 wire B. & S. gauge. On the other hand, if the same method and the same line conditions are supplied in the case of the direct-current system, the figures present themselves as follows, with a 10 per cent. drop and a pressure of 500 volts: C. M. = circular mils. Amperes = 100,000 watts ÷ 500 = 200.

$$\text{C. M.} = \frac{5{,}280 \times 200 \times 12}{50} = 253{,}440,$$

or a wire which could only be strung as a stranded cable (Fig. 3), as its size would be more than No. 0000 B. & S. gauge, or about 24 No. 10 wires in circular mils. Comparing this cross-section of copper with that of the first, means 253,440 ÷ 15,840 = 16 times. This result shows that, for a half-mile run, it is not practical to use 16 times as much copper in one case as in another. As two conductors are employed in each circuit, the total weight of copper would be really that of one mile of each of the given sizes.

Pressures of Standard Generators.—The outside demand has largely contributed to the adoption of certain standard pressures. These run as follows with direct- and alternating-current generators:

Direct current.	Alternating current.
Generators of	Generators of
125 volts.	2,200 volts.
250 "	6,000 "
550 "	10,000 "
600 "	15,000 "
1,000 "	20,000 "
2,000 "	30,000 "
2,500 "	40,000 "
3,000 "	60,000 "

In this table with the last four quotations of 1,000, 2,000, 2,500, and 3,000 volts direct-current machines for high-tension arc lighting are kept in view. The last calculation, showing the difference in sizes of conductors for 500 direct and 2,000 volts alternating, would necessarily become the same if a high-tension direct-current system were introduced. But although this system would serve and be less expensive than the alternating for street lighting, it could not be employed for hall or residential lighting on account of the great danger involved.

Capacity of Machines.—The use of either alternating- or direct-current generators calls for a knowledge of what is to be expected of them when under heavier strain than usual. The overload factor, in other words, is a point of first importance in their purchase. According to the recommendations of the American Institute of Electrical Engineers, in its

Standardization Report, the ability of a generator to be overloaded 25 per cent. without its windings rising in temperature more than 27 degrees F. over the normal temperature of full load, or 50 per cent. for a short period of time without destructive sparking, is a sign of the value of the generator to meet the conditions of service. The questions relating to the best conditions under which electric lighting can be begun are not more important than those which relate to the qualifications of a machine to perform its functions in this field of engineering.

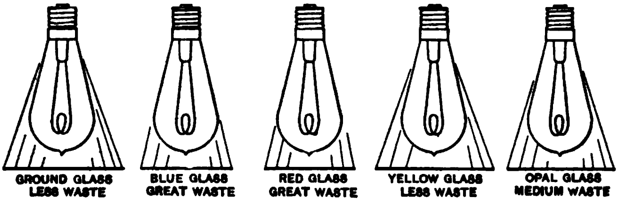


FIG. 4.—Light Wasted with Different Screens.

Selection of Lamps.—The distinction to be drawn between one form of lighting and another is largely determined by the character of the illumination in view. From a broad standpoint, the difference is that of interior from exterior lighting. The lighting of office-buildings, theaters, large halls, and private dwellings differs in the nature of the lamp required when compared with the street. In the first case, many small centers of illumination become the means by which a comparatively uniform degree of lighting is secured. In the second case, more intense centers of illumination are the foundation for an outside system, by which the streets of a city are lit up over a series of contiguous areas. In the majority of cases where lighting is done the light is so developed that it falls directly upon the areas to be brightened. The light is not, as a rule, cast upon a given surface and then reflected downward or sideways. It is the object of lamp manufacturers to avoid, as far as possible, the dispersion of light, or its undue absorption through an inefficient and unscientific method of distribution. Although globes of all shades and colors are brought into commission, their use is only necessary because of the disagreeable intensity of the light and the desirability of shading or toning it down. Different colors are effective, from an æsthetic standpoint, in the production of pleasing hues; but any method which affects the color (Fig. 4) also diminishes the light. Ground glass, as well as opalescent shades or globes, is very wasteful in this respect. The resulting condition of affairs in the lighting field is somewhat illogical, for the reason that knowledge and skill are brought into play to develop a highly efficient generating, transmitting and distributing system with regard to the electrical energy involved; and this, when transformed as far as possible into light, is permitted to pass through globes and screens by which from 10 to 40 per cent. or over is wasted. Meter measurements, indicating excellent judgment in the method of generating electricity when contrasted, in some instances, with the returns obtained from candle-power measurements, seem to show light losses of a serious nature. A given amount of power is productive, with modern lamps, of a given amount of light. In other words, a certain weight of kerosene oil, from which a horse-power could be obtained if exploded in a gas-engine; a certain number of cubic feet of illuminating gas similarly utilized; a given weight of coal burned in a steam-boiler, or oil used as fuel for the same purpose; a horse-power of mechanical energy obtained from a waterfall—all of these are sources of power which, with respect to lighting, produce a certain amount of candle-power. Power therefore represents light when so transformed; and it merely becomes a question of the means or mechanism employed as to whether the transformation results in more or less light. Using screens or shades, however, which absorb a heavy percentage of the light is equivalent to using defective machinery in the way of inefficient boilers, engines, dynamos, or conductors, causing too heavy a line loss.

Returns from Generators.—Generators of different horse-power vary with respect to the returns they give when set into operation. A 1-hp. dynamo is necessarily less efficient than a 1,000-hp. machine. The percentages of efficiency increasing with the capacity of the generator is to be expected, as shown by the following table:

Power of generator in kilowatts.	Percentage of efficiency.
1	60 to 70
5	70 " 80
10	80 " 90
15	85 " 90
20	87
25	89
30	90
40	91
50	92
60	92.5
80	92.5
100	93.0
150	93
200	93.5
300	94
400	94.5
500	95 to 96
1,000	96 " 97

Cost of High Efficiency.—One of the best rules followed by conservative engineers is that of not reaching out for a too expensive efficiency. By this is meant the efforts made to overtop the market commercial efficiencies a few per cent., at a cost all out of proportion to the benefits gained. As an example of this false economy, suppose a generator costs $1,000 and possesses an efficiency of 90 per cent. If it costs the manufacturer an extra $200 to gain a few per cent. more, then whatever economic advantages are supposed to arise from the few per cent. additional efficiency, are lost through the following: First, the additional investment and the interest it represents; second, the additional difficulty of making sales through the higher price; third, the necessity for special attention to preserve the advantages paid for; and, fourth, the inability to control losses in light through its faulty manipulation when developed. For these, and perhaps additional minor reasons, the cost of high efficiency is sufficiently prohibitive, when obtained by too heavy an additional investment, to be a practical commercial proposition. The durability and amount of care required to give uniformly good returns are the governing influences in the selection of dynamos and motors. For equal investments, the machine of the most solid construction is by far the better choice.

Elements of Power.—The method of calculating electric power is based upon the pressure in volts and the current in amperes. These are the elements of power for either direct or alternating currents. In the case of a direct or continuous current, both the volts and amperes operate as elements of power simultaneously. In the case of an alternating current, the volts and amperes may not operate simultaneously as elements of power. For this reason, in the latter case the amount of power is calculated with reference to that condition or conditions which prevent the co-operation of the pressure and current at the same time.

Continuous Current Calculations.—For measuring the pressure in volts or the current in amperes both volt and ampere meters are employed. These instruments are so devised that the current passing through produces a magnetic field. The extent to which this field is manifested is, in a general way, the measure of the number of volts or amperes in the circuit.

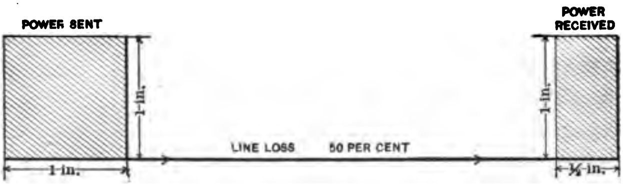


FIG. 5.—Sketch Showing Power Lost in Line.

For instance, in a voltmeter of the standard Weston make, more volts or less volts produce through its fixed resistance more or less current, which produces a stronger or weaker field, a stronger or weaker mechanical pull against a coiled spring, and, in consequence, a greater or less range of indication of the pointer showing the volts in the circuit. In the same manner an ammeter permits the current to operate similarly. Instead of the current passing through a low resistance in the voltmeter, the resistance is made as high as possible. By this means the voltmeter takes only sufficient current to actuate its mechanism. The resistance of a 150-volt reading meter of the Weston construction ranges from 10,000 to 20,000 ohms. The amount of current abstracted from the source being measured is thus reduced to a very low figure; sufficiently low to make no impression upon the records given by the ammeter when both instruments are in operation simultaneously on the circuit. The ammeter is constructed with just the opposite idea in view. Its resistance is made as low as possible, so that when current measurements are taken, its resistance is not the cause of drop in the instrument. For this reason the resistance of an ammeter will be as low as a few ten-thousandths of an ohm. In one instrument as little current as possible is consumed; in the other, as little of the voltage as possible is dissipated.

Power is measured in watts, or in quantities of a thousand watts at a time, called kilowatts. Watts are obtained by the product of volts and amperes. Taking a specific case, suppose 1,000 volts and 50 amperes are impressed upon a line of 10 ohms resistance. The power in watts and kilowatts, the drop, the watts wasted in heat, and the percentage of efficiency in the line as a conductor (Fig. 5) will be as follows:

Total power impressed upon the line = 1,000 × 50 = 50,000 watts.

Total power impressed upon the line = 50,000 ÷ 1,000 = 50 kilowatts.

Total power wasted as heat in the line = 25 kilowatts.

Total power delivered at the other end = 500 × 50 = 25,000 watts.

Total power delivered at the other end = 25 kilowatts.

Total power wasted as heat in the line = 50 × 50 × 10 = 25,000 watts.

Total power wasted as heat in the line = 25 kilowatts.

Total efficiency of the line = 25,000 ÷ 50,000, or 50 per cent.

Sources of Power.—A variety of sources of power exist, which may be variously classified for convenience. These sources of power may be natural, as those supplied by the earth, water, or air, or they may be artificial, that is, produced by mechanism and fuels of different character. As regards the natural sources of power, they may be arranged in the following manner:

I.—SOURCES OF NATURAL POWER USED BY MEANS OF MACHINES ADAPTED TO THEM

Air as utilized by means of windmills for developing rotation.

Water (falling) as utilized by means of water-wheels for developing rotation.

Waves as utilized by means of pumps for developing rotation.

Tide (if fast) as utilized by means of water-wheels for developing rotation.

Tide (if slow) as utilized by means of floats for developing rotation.

Sun's heat as utilized by means of mirrors and steam-engine.

II.—SOURCES OF ARTIFICIAL POWER USED BY MEANS OF MACHINES ADAPTED TO THEM

Coal as utilized by means of steam-engines, steam-turbines, and rotary engines.

Gas as utilized by means of gas-engines.

Oil as utilized by means of gas-engines, or for producing steam.

Wood as utilized by means of steam-engines.

Alcohol as utilized by means of engine specially constructed.

Compressed air as utilized by means of engine specially constructed.

As may be readily noted, this classification is more or less arbitrary, because of the difficulty of separating the purely natural from the artificial sources of power. But the line of distinction is somewhat strongly drawn by the fact that in the first case no heat is directly or indirectly applied by man; while under the second heading, heat or an explosive spark, or both, is produced, either at the beginning or end of the process. The use of windmills and water-wheels may be found throughout European countries as one of the first acknowledged sources of natural power; the first, in fact, to displace manual labor or that of animals. In Holland particularly, wind has served this purpose from time immemorial. In Switzerland, water-power came into frequent employment, the source being the mountain-torrents formed by the melting of ice masses or prehistoric glaciers.

In the neighborhood of the Jersey coast, experiments have been conducted with wave-motors. (Fig. 6) built upon unique lines. The oscillating and up-and-down movement of the waves is employed to operate a series of small pumps. These pumps force water into a huge tank against considerable air-pressure. The water thus pumped in is under such pressure that when permitted to escape it is capable of operating a water-wheel or turbine in the same manner as a stream falling from a height productive of the same impact. The quantity of power obtainable on this basis makes it a proposition of great interest. The erection of strong steel supports and other means of resisting the violence of the sea, constitutes an item of expense that merits conservative consideration. A few figures in connection with wave-power will be of interest.

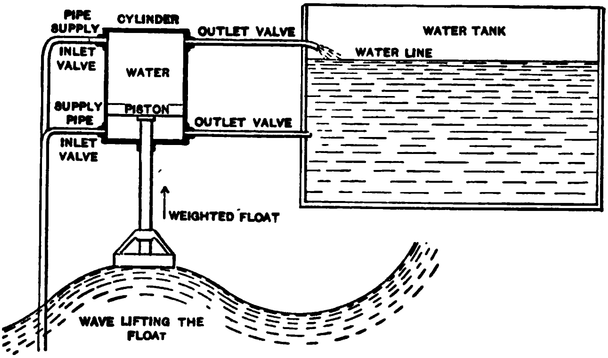


FIG. 6.—Principle of a Pumping Wave-motor.

Power from Waves. — A cubic foot of water weighs 62.5 pounds. If it is lifted 5 feet and then permitted to fall, each operation will call for a manifestation of mechanical power equal to $5 \times 62.5 = 312.5$ foot lbs. The total energy is equal to $2 \times 312.5 = 625$ foot lbs. A wave rising and falling once every one, two, or five seconds would rise and fall 60, 30, or 12 times a minute. With these figures as a foundation, the foot lbs. developed are equal to 60×625, 30×625, or 12×625; equal respectively to 37,500, 18,750, and 3,900 foot lbs. per minute. As there are 33,000 foot lbs. per minute to a horse-power, these cases represent conditions productive of more than 1 hp., ½ hp., and $\frac{1}{10}$ hp. In a vertically situated pump, whose piston-rod is weighted to keep the piston down until lifted by the advancing wave, a series of reciprocations will be possible, the power of which can be readily estimated. The wave must lift the piston-rod, in this case, through the medium of a buoyant mass attached to it, yet sufficiently heavy to drop downward when relieved of the force of the wave. Along a hundred feet of shore-line devices of this kind properly arranged would easily operate and pump water into the receiving reservoir at all times. It is a matter of simple calculation to see how large a source of power can be derived from a system of this character. It would not be too far-fetched a statement to make to say that along the Atlantic coast millions of available horse-power in this form could be turned to a useful purpose.

CHAPTER II

POWER FROM THE SUN.—VACUUM-TUBE LIGHTING.—AMOUNT OF LIGHT PER INCH OF TUBE.—EFFICIENCY.—LIGHT AND LAMP EFFICIENCY.—SHORT LIFE WITH HIGH EFFICIENCY.—ANOTHER FEATURE OF HIGHER LAMP EFFICIENCY.—COST OF POWER.—COST OF POWER IN VARIOUS LOCALITIES.

Power from the Sun.—Although it is not a difficult proposition to prove that all forms of energy known originated in the sun, as far as the solar system itself is concerned, it is of great interest to observe the trend of the efforts made to utilize the sun's rays directly. Ericsson was among the first to advance the idea of the sun-motor. By this is meant an engine so constructed that the action of the sun's rays will heat a steam-generating section and thus develop power and rotation. In fact, the engine is simply a specially constructed steam-engine, the principal part, the boiler in this instance, representing the focus of such of the sun's rays as are gathered up by specially constructed mirrors. It is obvious that the amount of heat transmitted by the sun reaches into figures almost beyond computation. By this is meant the heat energy, not the light, though both can be categoried on this basis. Light is the one item which, so far, cannot be either transformed or stored, as may other forms of energy. The only illustration of this action widely known is that of the plant in manufacturing chlorophyll by the action of light. In this respect, because coal is a product of vegetation and vegetation a consequence of light energy being absorbed, coal itself becomes in this sense stored sunlight. The action in this case is one in which light acts as an agent in producing changes in the chemical constitution of vegetal matter.

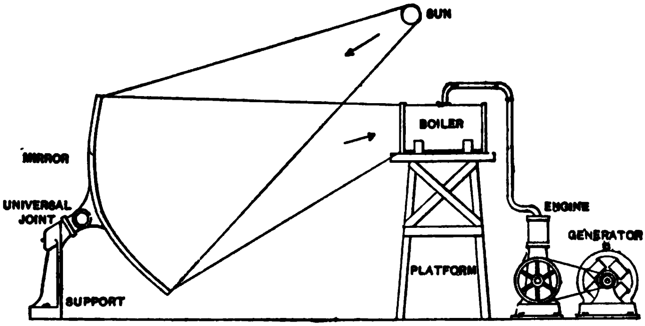


FIG. 7.—Method of Utilizing the Sun's Heat for Generating Electricity.

The utilization of the sun's heat directly by means of concave mirrors (Fig. 7), which focus the heat rays, which direct them upon a boiler, which generates steam, which develops rotation by means of an engine, which gives power for driving a dynamo, and which finally permits the storage of electrical as chemical energy in storage batteries, is an illustration of the different channels through which energy can pass before emerging in the form in which it is to be finally utilized. In this instance, at night, the current could be employed for lighting, and thus a certain percentage of the original ether waves again transformed into light and heat.

Estimates have been given of the amount of energy radiated by the sun upon a square foot or yard of the earth's surface. It is unnecessary to state that the light is of a brightness unsurpassed by the most brilliant sources of illumination at present in service. Depending upon the position of the sun's rays, whether at early morning, noon, or later, the degree of heat and consequently the energy available at a given locality would vary. At the equator it might rise to $\frac{1}{4}$, $\frac{1}{2}$, 1, or more horse-power per square yard. At the Tropic of Cancer or Capricorn it would be less, until the temperate zones were reached, where it would be fairly uniform. The great Sahara Desert represents in this respect a source of power as difficult to measure as the tidal or wave forces of the world. At the low estimate of $\frac{1}{4}$ hp. in heat energy per square yard for 5 hours a day, this desert would yield from a square 100 miles in length by 100 miles wide the following:

100 miles = 5,280 ft. × 100 = 528,000 ft.
100 miles × 100 miles = 528,000 × 528,000 = 278,784,000,000 sq. ft.
1 sq. yd. = 3 × 3 = 9 sq. ft.
278,784,000,000 ÷ 9 = 30,976,000,000 sq. yds.
At $\frac{1}{4}$ hp. per sq. yd. 30,976,000,000 sq. yds. produce $\frac{1}{4}$ × 30,976,000,000 = 7,744,000,000 hp.

for 5 hours the output would be 38,720,000,000 hp. hours.

Vacuum-tube Lighting. — A form of lighting which offers some relief from existing methods, in that no actual incandescence of solid matter takes place, is found in the vacuum tube. The usual method of producing light is to heat to whiteness a certain body of material, usually carbon, and from the radiation thus secured obtain enough light for practical purposes. In burning ordinary illuminating gas, a flame consisting of millions of carbon molecules heated to comparative whiteness creates the illumination so widely employed. In the use of acetylene, the gas is also capable of producing an incandescent screen of white-hot material; but a whiter light due to a higher temperature results. In the Welsbach burner the heat of the flame is increased by permitting air to enter at the base and produce a Bunsen flame, which plays upon a screen of rare oxide composing the mantle.

The incandescent lamp is an obvious case of the electrical energy producing heat directly in the filament. The principle that in proportion to the resistance of the conductor, however good or bad, the energy is degraded into heat, holds true here in a striking manner. The effort is made to degrade all of the energy the carbon filament by its resistance can transform into heat. From the heat thus produced the amount of light, variously rated as 16 or 32 cp., as a usual thing results. But the carbon is the form of solid matter upon which the current operates, heating it, as in the gas or acetylene flame, and secondarily producing light. The arc lamp is a similar instance of where the arc formed between the carbon terminals is composed of carbon molecules, which permit the current to jump across, and in so doing are so raised in temperature that the characteristic dazzling brightness appears. The screen in this case is a mass of carbon particles, probably molecular, heated to vivid incandescence, as in the previous cases referred to. The vacuum-tube system of lighting, as now in evidence, consists of a long glass tube of 2 or 3 inches diameter and 10, 20, or even more than 50 feet in length. This tube contains either a partial vacuum or a gas of secret nature, but capable of transmitting the energy imparted to it from end to end. The tube is supplied at both ends with electrodes, which impart the electricity to the gas or remaining air contained within. The ensuing process is of a different character to those outlined. The gas molecules become the carriers of the energy, and, being charged, act in every respect like other light bodies affected by static influences. The individual charges are sufficient to cause extreme repulsion and agitation among the molecules. They move backward and forward with extreme rapidity, colliding frequently. The extent of the collisions is, in some respects, a measure of the amount of light produced. Thus, the entire problem of vacuum-tube lighting resolves itself down to a case where the original energy is utilized to create free molecular motion over a large path (Fig. 8), with the average result that a great number of impacts take place between the carriers. The greater the number of moving molecules, and the faster they move, the greater the number of impacts and the greater the degree of illumination resulting.

This device is placed around a room, at about the meeting of the wall and ceiling, as one long glass

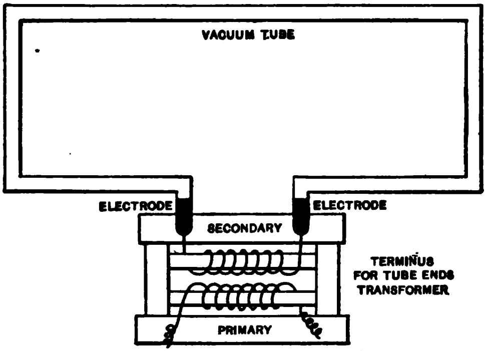


FIG. 8.—General Principle of Vacuum-tube Lighting, Showing Use of Transformer.

tube, whose two ends enter a box communicating with the source of electric current. The current used is alternating, and is transformed until it reaches a high potential. It is obvious that the potential in this case must bear a direct relationship to the length of the tube. The longer the vacuum tube, the greater the pressure required to cause a uniform degree of illumination to appear.

Amount of Light per Inch of Tube.—The system calls for the use of a photometer, by means of which light measurements are taken of any inch length (Fig. 9) of the tube. This device gives such results that the failure of the tube to render a normal amount of light is readily detected. In this system a method of joining the glass has been developed, by which it may be lengthened, reduced, or repaired with facility. Another feature is one by which it can be exhausted or readily resupplied with the gaseous constituents necessary for the production of light. In all systems developed on these lines the integrity of the vacuum is of first importance. Unless it is preserved, the candle-power will vary with every change of this kind. At the end of a given length of run the advantages consist of the following: First, it is not necessary to reinstall new lighting apparatus to replace the old; second, it is claimed that the rehabilitation of the system is not a matter of great expense; third, the form of illumination is

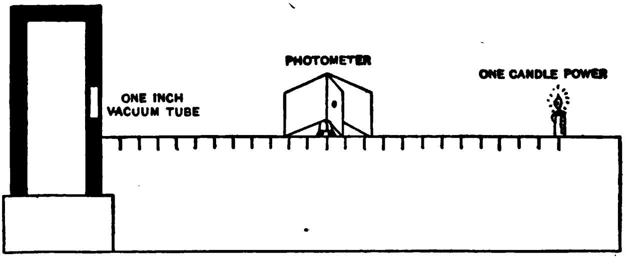


FIG. 9.—Method of Getting Candle-power of One Inch of Vacuum Tube.

such that the various degrees of light are admirably mixed in the proportions which insure an agreeable light impression; fourth, because no actual wear takes place of any particular part, the tube may be readily and permanently adapted to the walls of the room, hall, theater, or place of worship; the cost of the first installation is fixed; changes in the system would only amount to a new distribution of the light; fifth, the light within the tube is not of an intensely brilliant character, but subdued and non-irritating. It deserves the name given it—artificial daylight.

Efficiency.—The power consumed is not in excess of that required for the incandescent-lamp system. Per unit of light, the watts required range from 3 to 4, that is, per candle-power. The incandescence of the gas particles within the tube, brought about by their motion, may eventually reach a point, by the use of a particular gas, where very little power will excite intense agitation. The elimination of heat is accomplished more thoroughly in this system than in any other in vogue. Heatless light, if properly produced, would mean an economic revolution. A gas-jet gives about 1 per cent. or less return in light from the gas consumed. This means a waste of over 99 per cent. of the gas, as far as this object is concerned. A 16-cp. jet taking 5 cubic feet per hour would therefore give $99 \times 16 = 1{,}584$ cp. at an efficiency of 100 per cent. Light is therefore wasted to an immense degree because the present methods are primarily heat- instead of light-producing. Comparing the various sources of light gives the following:

COMMON ILLUMINANTS

First—Torch of resinous wood as a source of illumination, approximately 1 hp. per 16 cp.

Second—Candle made of wax, such as paraffin, approximately $\frac{3}{4}$ hp. per 16 cp.

Third—Kerosene-oil lamp, approximately $\frac{5}{8}$ hp. per 16 cp.

Fourth—Lamp using illuminating gas, approximately $\frac{1}{2}$ hp. per 16 cp.

Fifth—Welsbach mantle, approximately $\frac{3}{8}$ hp. per 16 cp.

ELECTRICITY

Sixth—Incandescent lamp, approximately $\frac{1}{10}$ hp. per 16 cp.

Seventh—Vacuum-tube lighting, approximately $\frac{1}{10}$ hp. per 16 cp.

Eighth—Arc lamps, approximately $\frac{1}{100}$ hp. per 16 cp.

The above figures are arbitrary, but they present a relative view of the amounts of energy consumed to give light. The amount of heat in the carbon when oxidized, considered as a definite amount of energy, covers the first five cases. Those that follow use electricity; if the power price paid for this is estimated from the fuel itself, then the energy consumed in producing electric light would be large in spite of the use of improved and expensive machinery.

Light and Lamp Efficiencies.—The amount of light obtainable from a horse-power or kilowatt of electrical energy is not limited by theory, as it is by practice. The ordinary 16-cp. lamp is only a stepping stone to better forms of illumination, as far as power consumption is concerned. It is not to be forgotten that the incandescent lamp, which now takes from 3 to 4 watts per candle-power, has been built to take only 1 watt per candle-power, though under such circumstances its durability becomes a matter of great question. The following table illustrates the amount of light produced by 1 hp. and 1 kilowatt of electricity (Fig. 10) by lamps consuming various wattages per candle-power:

TABLE OF LIGHT PER POWER UNIT.

Watts per candle-power in lamp.	Candle-power per kilowatt.	Candle-power per horse-power.
5	200.0	149.2
4.5	222.2	166.0
4.0	250.0	186.5
3.5	285.7	213.0
3.0	333.33	248.6
2.5	400.00	294.4
2.0	500.00	373.0
1.5	666.66	497.3
1.0	1,000.00	746.0
.5	2,000.00	1,492.0

Short Life with High Efficiency.—The carbon will not last if pushed to too great a temperature in giving light. The use of only 1 watt per candle-power in lamp construction represents so great a risk that no guarantees of any description are given with such lamps by the factory. Only lamps using rare oxide filaments are expected to have so great an efficiency and still possess durability. The economic side of the question is best presented by means of another table, in which the number of lamps rated at 16 cp., which might be used per horse-power or kilowatt on this basis, are given:

Number of 16-cp. lamps per horse-power.	Number of 16-cp. lamps per kilowatt.	Watts per candle-power.
9.32	12.50	5.0
*10.40	14.00	4.5
*11.60	15.62	4.0
*13.30	17.8	3.5
*15.50	20.83	3.0
18.40	25.00	2.5
23.31	31.25	2.0
31.00	42.00	1.5
47.00	62.50	1.0
93.25	125.00	.5

The figures marked with a star are those which lie within the range of general electric-light practice, representing the use of lamps whose watt consumption per candle-power varies from 3 to 4.5. Along the line of figures giving 1.5 watts per candle-power may be found, under the heading of lamps per horse-power and per kilowatt respectively, 31 and

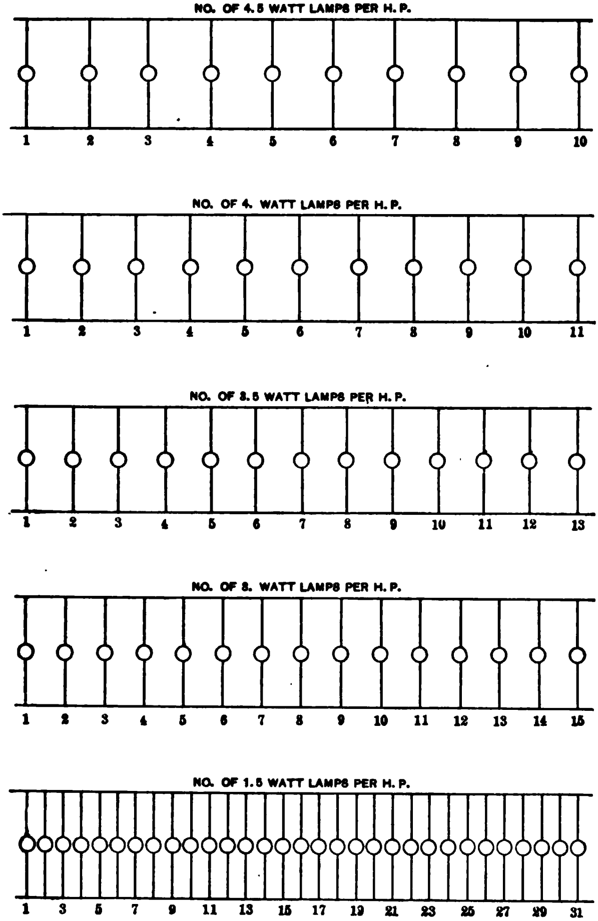

NO. OF 4.5 WATT LAMPS PER H. P.
1 2 3 4 5 6 7 8 9 10
NO. OF 4. WATT LAMPS PER H. P.
1 2 3 4 5 6 7 8 9 10 11
NO. OF 3.5 WATT LAMPS PER H. P.
1 2 3 4 5 6 7 8 9 10 11 12 13
NO. OF 3. WATT LAMPS PER H. P.
1 2 3 4 5 6 7 8 9 10 11 12 13 14 15
NO. OF 1.5 WATT LAMPS PER H. P.
1 3 5 7 9 11 13 15 17 19 21 23 25 27 29 31

FIG. 10.—Increasing Capacity of 1 Hp. to Give Light with Lamps of Higher Efficiency.

42. A lamp which in electric-light practice takes only 1.5 watts per candle-power will be the means of increasing the available number of 16-cp. lamps of the regular type from 15 or 20 to 30 or 40. It is not a difficult matter to imagine the advantages of this to a station whose capacity is tested to the limit—a station, for instance, in which the generators can only supply 10,000 16-cp. lamps under ordinary conditions, but which actually has its capacity increased by the use of more efficient lamps to the extent of being able to double its lighting as far as the number of lamps are concerned. From the economic standpoint already referred to, the station income is by such means so greatly increased that the engineering side of it becomes rapidly transformed into a financial advantage of large dimensions. To further accentuate the benefits arising through the use of efficient lamps, the case of a 1,000-light station is given, in which the increase in lamps is tabulated as the watts per candle-power are diminished:

CAPACITY OF A 1,000 16-CP. STATION UNDER DIFFERENT CONDITIONS.

Supplying power to	Lamps.
3.5-watt lamps...........................	1,000
3.0 " "	1,166
2.5 " "	1,400
2.0 " "	1,750
1.5 " "	2,333
1.0 " "	3,500

The reason why so many different efforts have been made to produce a lamp so much more efficient than the one in general use is largely found in the above figures. A station supplying power to light 1,000 lamps could, by the introduction of a lamp whose efficiency is represented by any of the figures given, increase its lighting capacity 50, 100, 200, or 300 per cent.

Another Feature of Higher Lamp Efficiency.—The cost of a lamp whose renewal is more frequent because of its higher efficiency also calls for consideration. If a higher-efficiency lamp burns only half the time of a lower-efficiency lamp, but during that time takes only half the power of the second lamp, the question arising is this: In comparing the value of the power saved with the value of the lamp, is there an advantage or a loss? For instance, if a lamp costs one dollar, but it saves one dollar's worth of electricity, is there any gain in the experiment? The answer is best given in the form which takes into consideration the fact that the station has been able to double its capacity as a source of electricity for lighting. The earning power of the plant has been doubled because it can double its customers with the additional expense of only doubling its lighting facilities outside. If the cost of the lamp is prohibitive, because its replacing is too expensive, then the advantage of a higher efficiency is lost.

The advantages are best set forth, however, in a table showing the increase in the income of a plant

(Fig. 11) on the supposititious basis of about $1 a month per 16-cp. lamp:

Increase in income of a 1,000 3.5-watt-lamp plant. Dollars increase per month.	Number of lamps of higher efficiencies.
$1,000	1,000 3.5-watt lamps.
1,166	1,166 3.0 " "
1,400	1,400 2.5 " "
1,750	1,750 2.0 " "
2,333	2,333 1.5 " "
3,500	3,500 1.0 " "

Any form of engineering or finance that can make a given condition become more productive is unquestionably superior to that originally prevailing. In the application of electricity to certain purposes, like electric light or power, a guidance in doing things is often best obtained by reference to the ultimate purpose of the enterprise. In electric-lighting particularly the two important features which present themselves are, first, the cost of the power, and, second, the amount of light from a given amount of power.

Cost of Power.—The cost of fuel is only one part of the cost of power. The more expensive the machine in which fuel is burned the more expensive is the act of consuming it. But the expensiveness of a machine is always proportional to its economy in such fields of engineering as relate to electric-light and power work. In other words, the manufacturers of very economical devices believe that the saving due to the devices exploited should be partly divided. For this reason highly economical forms of apparatus due to special inventive talent, that necessitated costly experimenting to produce, are also expensive. A high-grade boiler, engine, or generator calls for an investment larger than one of inferior grade. In electric lighting the best of machinery is generally employed, because the saving qualities of certain classes of apparatus are such that the annual gain by their use far outweighs the additional expenditure necessary by their purchase. Burning coal in a high-grade boiler means the combustion

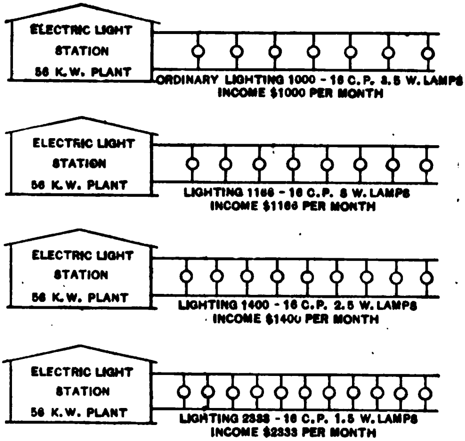

ELECTRIC LIGHT STATION 56 K.W. PLANT
ORDINARY LIGHTING 1000 - 16 C.P. 3.5 W. LAMPS
INCOME $1000 PER MONTH
ELECTRIC LIGHT STATION 56 K.W. PLANT
LIGHTING 1166 - 16 C.P. 3 W. LAMPS
INCOME $1166 PER MONTH
ELECTRIC LIGHT STATION 56 K.W. PLANT
LIGHTING 1400 - 16 C.P. 2.5 W. LAMPS
INCOME $1400 PER MONTH
ELECTRIC LIGHT STATION 56 K.W. PLANT
LIGHTING 2333 - 16 C.P. 1.5 W. LAMPS
INCOME $2333 PER MONTH

FIG. 11.—Increased Capacity of a Plant with Low-watt Lamps.

of fuel in a device whose original cost is great enough to make it and the other elements of the station constitute a heavy investment; the interest which must be earned to make this investment a financial success is earned by the coal when its energy is transformed into heat, steam-power, electricity, and electric light and power. The cost of power depends, therefore, upon the two items—of cost of fuel and extent of the investment (Fig. 12) for machinery, real estate, conductors, lamps, etc. An illustration of this fact can be drawn from the following table covering various degrees of investment:

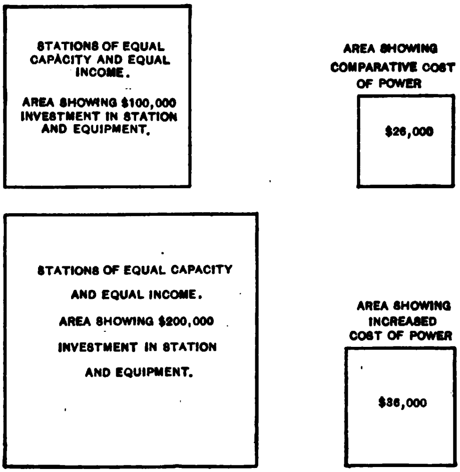

STATIONS OF EQUAL CAPACITY AND EQUAL INCOME.
AREA SHOWING $100,000 INVESTMENT IN STATION AND EQUIPMENT.
AREA SHOWING COMPARATIVE COST OF POWER
$26,000
STATIONS OF EQUAL CAPACITY AND EQUAL INCOME.
AREA SHOWING $200,000 INVESTMENT IN STATION AND EQUIPMENT.
AREA SHOWING INCREASED COST OF POWER
$36,000

FIG. 12.—How a Heavy Investment Increases the Cost of Power Relatively per Unit.

Cost of fuel per annum.	Cost of station.	Interest on investment at 6 per cent.	Cost of fuel and interest.
$10,000	$100,000	$6,000	$16,000
10,000	200,000	12,000	22,000
20,000	300,000	18,000	38,000
20,000	400,000	24,000	44,000
30,000	500,000	30,000	60,000
30,000	600,000	36,000	66,000
50,000	700,000	42,000	92,000
50,000	800,000	48,000	98,000
100,000	900,000	54,000	154,000
100.000	1,000,000	60,000	160,000

The above table is not statistical, neither is it based upon calculations derived from data relating to electric-light practice. It simply illustrates the idea of the increasing cost of power, though the fuel does not increase in price per ton with the increased heaviness of the investment for machinery, real estate, conductors, etc. If, for instance, the cost of one station is $100,000, as compared with the cost of another station of $200,000, and both produce the same amount of power, require the same number of employés, and have the same number of customers for light and power—then, with equal efficiencies, the power of one station costs much more than the power of the other to produce. This can be illustrated in the following estimate, in which $10,000 worth of coal is supposed to be burned up in each per annum:

Investment of $100,000.		Investment of $200,000.	
Interest	$6,000	Interest	$12,000
Fuel	10,000	Fuel	10,000
Labor	10,000	Labor	10,000
Total	$26,000	Total	$32,000

As all the expenditure each year, as well as each month, week, and day, is for the purpose of producing light and power at the other end, it is quite evident that the spending of large sums in the installation and equipment will mean a greater cost for power, unless it is recognized that the best of judgment was used in making the expenditures, and that they were made for indispensable elements of the plant.

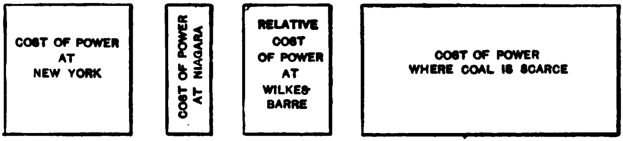


FIG. 13.—Relative Effects of Locality Upon Cost of Power.

Cost of Power in Various Localities.—Localities have a great influence upon the cost of power per horse or per kilowatt. At Niagara Falls neither the ground nor the power itself is a source of heavy expense. In New York City the same amount of power (Fig. 13) would mean large investments for costly real estate, for coal, and for conduits for the subterranean conductors. In the neighborhood of coal-mines, where fuel is cheaper because of the saving in freight, power would be cheaper. The cost of power is in many respects largely proportional to the investment required to produce it.

CHAPTER III

METHODS OF DISTRIBUTING ELECTRICITY.—DISTINGUISHING DIFFERENCES.—OUTLINE OF ALTERNATING- AND DIRECT-CURRENT SYSTEMS.—POSITION OF CENTRAL STATION.—THE CENTRAL STATION IN PRACTICE.—GENERAL USE OF POLYPHASE CURRENTS.—DISTRIBUTION BY WIRE.—A TWO- AND THREE-WIRE SYSTEM CONTRASTED.—THE POWER-FACTOR.—ANGLE OF LAG.—SELF-INDUCTION.—LINES OF FORCE SURROUNDING A CIRCUIT.—MEANING OF ANGLE OF LAG.

Methods of Distributing Electricity.—The evolution of the incandescent lamp led to further development in methods of distributing electricity for light and power. At the same time the dividing line between the engineering field devoted to direct current and the engineering field devoted to alternating current became more and more eliminated. Electricity is developed at present in two ways:

First—By means of direct-current machinery.

Second—By means of alternating-current machinery.

The apparatus employed in each case naturally led to a difference in the methods of distributing the electricity. In the first place the continuous current is generated and led directly, through the medium of large conductors, to the street and past thousands of homes and business establishments. In the second place, the electricity generated at a dangerously high pressure is led, by means of small conductors, to points where its distribution is required; and then, by means of transformers, lowered in pressure and led into places where it is to be used.

Distinguishing Differences.—Taking the point of view of labor and expense, the situation presented is that of one system using more copper because of a low-pressure direct current being employed for incandescent lamps, arc lamps, and motors; and the other system employing a high-tension alternating current, which is not distributed directly, but indirectly, by means of transformers, to the points where it is to be consumed. These distinguishing differences are at present of importance, because the outline of each system in this respect shows the extent of its adaptability to large or small cities. An outline of each system will also serve to show where they may be advantageously combined, as already suggested, and as they are combined in large central stations.

Outline of the Alternating- and Direct-current Systems.—The alternating-current system in outline makes use of the following elements to compose the system as a whole:

ALTERNATING-CURRENT SYSTEM

1—The Alternator. 2—The Exciter. 3—The Switchboard. 4—The Transformer. 5—The System of Distribution. 6—The Motors, Arc Lamp, and Incandescent Lamp.

The reference made to the lamps and motors is in order to present the idea that the system can operate motors if their construction is adapted to the character of the alternating current employed. In this respect the additional items must be added, entitled: First, single-phase; second, two-phase; and, third, three-phase currents. Each of these currents will operate arc and incandescent lamps, and each can operate motors, provided they are constructed so as to fall within the classification of single-, two-, or three-phase motors.

The direct-current system is simpler, in the respect at least that the electricity is not transformed after leaving the central station as regards its pressure. Its elements are as follows:

DIRECT-CURRENT SYSTEM

1—The Generator. 2—The Switchboard. 3—The System of Distribution. 4—The Motors, Arc Lamps, and Incandescent Lamps.

It is evident that the absence of any sub-generator to the dynamo in use, and the absence of transformers, are illustrative of the directness of this system. The conductors practically lead directly from the generator (Fig. 14) to the consumer via the station and street or overhead wires. In the alternating-current system, however, the metallic connection between the station and the consumer ends in the primary or—in this case—the high-tension coil of

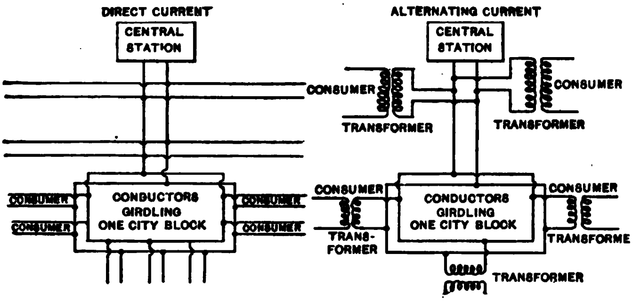


FIG. 14.

Complete Metallic Connection to Consumers from the Central Station.

Metallic Connection to Consumer, Not Complete.

the transformer. At this point the inductive relation begins. The consumer's light and power in this system is derived from a coil simply placed in juxtaposition to the other coil whose extremities connect with the station. There is no metallic connection, no direct electrical connection, but merely an inductive relation supplied between the station and the consumer. In showing these two systems of supplying electricity for light and power from a central station, or a station deriving its power from a larger and more distant station, the characteristics of the alternating will appear, emphasizing the discontinuity metallically, but likewise indicating the continuity with the direct current. The reason for this difference is found in the peculiarities of the two currents. The energy of one can be transmitted readily through a large enough conductor and used as it is transmitted. The energy of the other is transmitted through a smaller-sized wire, and is either used at the beginning or end of the circuit, or both, to create inductive action. This causes the condition to exist of a system composed of a series of separate parts at the points of metallic separation, while associated only inductively. This condition is imposed by the fact that the transformation of the pressure of an alternating current up or down can only be caused practically by inductive action.

Position of Central Station.—The central station must be regarded as a reservoir of electricity distributing the energy to the different customers in the neighborhood. The position of this reservoir, therefore, with regard to these self-same customers, must be such that a minimum of power is wasted and the least possible amount of copper utilized. In other words, the lines are not laid carelessly or purposelessly, but are placed in certain locations with regard to the central source of energy so as to attain these objects.

If, for instance, a series of city blocks are taken into account, forming a square-shaped area (Fig. 15), it is quite evident that the best position for the central station is that formed by the intersection of two diagonals from the corners of the square. On the other hand, if the city area is circular, the center of it would be approximately the best position for the station. The presumption is, in each of these, or in other cases, that the demand for lighting is nearly uniform. By this is meant that either the list of customers is one which gives a uniform distribution, or other indications lead to the conclusion that the lighting will eventually become uniformly distributed. In this case, whether the current used be alternating or direct, the best possible position for the central station is one in which it is about the same average distance from certain distinct groups of consumers. If the customers were grouped in a circular area, the center of this area for the central station would place the customers in a series of concentric bands. Or, if the area of current distribution is square, the position of the central station is likewise determined as that approaching the center of the listed customers.

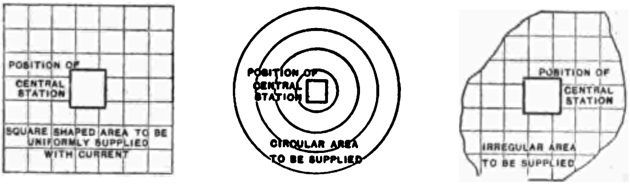

POSITION OF CENTRAL STATION
SQUARE SHAPED AREA TO BE UNIFORMLY SUPPLIED WITH CURRENT
POSITION OF CENTRAL STATION
CIRCULAR AREA TO BE SUPPLIED
POSITION OF CENTRAL STATION
IRREGULAR AREA TO BE SUPPLIED

FIG. 15.

Customers Occupying Places Forming a Square-shaped Area.

Customers Occupying Places Forming a Circular Area.

Customers Occupying Places Forming an Irregularly Shaped Area.

The Central Station in Practice.—A large city may not present a case where it is economical to feed all conductors from one center. For this reason a series of centers are inaugurated (Fig. 16), from which conductors lead to a given area of city blocks. A number of central stations would then be employed to supply the entire city with electricity; but it will be divided up in this case into sections or divisions, and each division will be treated as an independent case.

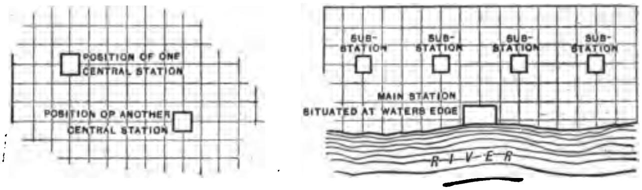


FIG. 16.

Two Separate Central Stations Employed for Electric Light and Power.

One Central Station with Auxiliary Sub-station Employed for Electric Light and Power.

Another method is that of having a single great station situated in a given position, either at the center or preferably at the edge of the city-line. From this point conductors are run to sub-stations situated where central stations proper would otherwise be necessary. The sub-stations thus constitute centers of distribution for a given area. They could be entitled distributing stations as regards their actual function. The idea in any case is to reduce the annual power loss in the distribution, and to minimize the primary outlay for copper. Another governing reason is the cost of real estate. A position near the water, such that coal-barges can anchor directly under the station and deliver their coal, is preferable to any. By this means the fuel cost, as far as the delivery is concerned, is held in check, and the water required for condensers, etc., readily obtained.

An examination of the conditions of lighting of any great metropolis discloses the fact that the elements employed are practically the same as would be installed for actual power transmission. The original energy may be developed at a pressure far too high for use without the aid of converters, the advantage being that the development of a high-pressure alternating current means a limitation, not only of the copper, but of the power, which would otherwise be wasted as well.

General Use of Polyphase Currents.—The simple alternating current is not sufficient for the purposes required of it. A motor built to operate on a single-phase circuit must either be started up by outside power, or its starting device is not one that shows other than an effort to meet this condition with certain complications.

A single-phase motor does not possess the widely recognized advantages of the two- or three-phase motors. For this reason, it was to have been expected that the polyphase current systems would ultimately represent the highest standards of power generation, transmission, and distribution. That they would predominate in all cases where large enterprises of this kind were projected is also a logical conclusion borne out by practical experience. At present the central stations in large cities are of a composite type, particularly New York. Both the polyphase system and that termed the direct-current are used in conjunction with one another. It is evident that as far as the economical handling of the electrical energy is concerned the polyphase occupies the most prominent position. The distribution is made in the shape of direct current. Not only does electric lighting gain great advantages by its use, in the way of copper, real estate for stations, and therefore the avoidance of an unusually heavy investment, but the system of power transmission is entirely dependent upon this form of electrical energy. The ease of transformation of three-phase into two-phase (Fig. 17), or *vice versa*, and the readiness and economy with which either of these is turned into direct current, have been the means of simplifying

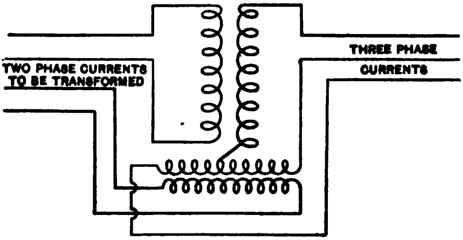


FIG. 17.—The Transformation of Two- into Three-phase Currents.

and making practical the handling of large quantities of power at distant points. A diagrammatic sketch of the transformation of two- into three-phase is added for reference.

Distribution by Wire.—The direct and alternating current are combined in all large schemes for the transmission and distribution of electrical energy. The reason why a distinction is made between the two processes is because one is, as its name implies, merely distribution. For this reason the machinery employed is not the same as that used in transmission. The other being transmission calls for a system which will give flexibility, efficiency, and economy in installation. Both the two- and three-wire systems of wiring may be utilized, although direct and alternating current respectively are employed—largely direct for the two- and three-wire, and generally alternating for the two-wire system only. The direct-current system of lighting is one whose distribution takes in the two- and three-wire, the calculations of wire sizes being based upon the following simple rule:

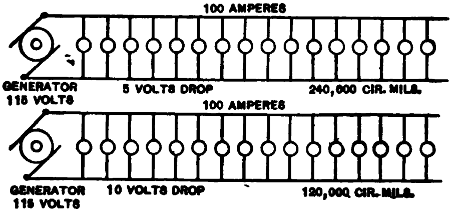


FIG. 18.—Effect of Doubling the Drop to Halve the Circular Mils.

Size of wire in circular mils = amperes × feet of wire × 12 ÷ volts drop. For instance, a line carrying 100 amperes with 5 volts drop through 1,000 feet of wire would require a size of wire equal to 100 × 1,000 × 12 ÷ 5 = 240,000 circular mils. For one-half the drop in volts (Fig. 18) the size of wire in circular mils is doubled. For one-quarter the drop, the size of wire in circular mils is quadrupled, as follows:

TABLE SHOWING THE CHANGE IN CIRCULAR MILS WITH CHANGE IN DROP.

Amperes.	Volts drop.	Length of wire.	Size of wire necessary in circular mils.
100	5	1,000 feet	240,000
100	2.5	1,000 "	480,000
100	1.25	1,000 "	960,000
100	10.00	1,000 "	120,000

The last line of figures, showing the halving of the size with a 10-volt drop, is given for the purpose of showing how flexible a matter the quantity of copper used may be with respect to the drop.

A Two- and Three-wire System Contrasted.—The purpose in using three-wire, instead of only two is for the advantage gained in the amount of copper employed and the better development of an electric-light system so based. It has been shown that in a simple two-wire system the amount of copper is entirely dependent upon the degree of loss sustained. The more willing the proprietors of a plant are to sustain a loss in power, in distribution, or in transmission, the less correspondingly is the amount of copper required. But in all such instances, if the saving in copper is $10,000, $20,000, or even $50,000, while the cost of the wasted power is, in the aggregate, after a few years have passed, an equal amount, then the saving and the cost are equal, and a new period is reached, where the loss through wasted power brings no compensation.

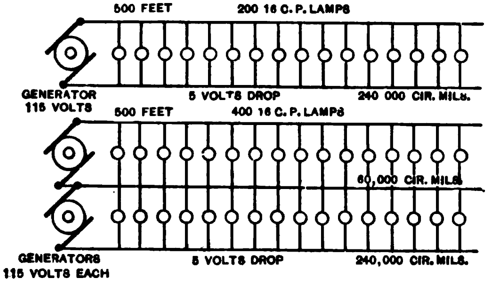


FIG. 19.—Comparison of Two- and Three-wire System, with Equal Current in Each, but Double the Lamps in the Three-wire.

Economy practised in this direction is, therefore, a failure in electric-light and power work. But in a three-wire system the drop can be regulated just as well as in a two-wire system, subject to the option of the designer of the circuit. A three-wire system carrying the same amount of energy as the two-wire (Fig. 19) can do a greater amount of lighting with less copper in proportion. For instance, in a two-wire system with a 5 per cent. drop as specified, on the basis of ½ ampere per 16-cp. lamp, the 100 amperes would light 200 lamps in a straight bank. But the size of wire would be 240,000 circular mils for the 1,000 feet of wire. On the other hand, if the 100 amperes are sent through a three-wire system, as illustrated, the result would be the lighting of 400 lamps with only the addition of a single wire to the circuit. This single wire in the middle need not have the cross-section of the others. It can be a wire of one-quarter the size, if some reasonable guarantee is given that the lamps are equally distributed on each side of the neutral wire. On this basis, the circular mils of the two-wire system are exceeded only to the extent of the copper in the neutral wire. The drop need not be greater, although double the voltage is used. By the same rule, in estimating sizes of wire, the circular mils equal 100 × 1,000 × 12 ÷ 5 = 240,000 for the two outside wires. The fact that 1,000 feet of wire are employed is proof that the run is only 500 feet in length. But the 5 volts drop is now divided up between two lamps, and amounts to only 2½ volts apiece. In other words, the 100 amperes and double the pressure, when sent through a three-wire system lighting 400 lamps of ½ ampere apiece, can do this lighting with the same drop in volts between the terminals. It is now carrying double the load, with the addition of a 500-foot wire of 60,000 circular mils. The middle wire only takes up the difference in current between one-half of the lamps on one side and the other. Its size may be even smaller than that recommended when a perfect circuit balance is established.

TABLE SHOWING THE CIRCULAR MILS OF A THREE-WIRE SYSTEM.

Lamps.	Amperes.	Volts drop.	Length of wire.	Size of wire in circular mils, including one-half the neutral wire.
400	100	5	1,000 ft.	240,000+ 30,000= 270,000
400	100	10	1,000 "	120,000+ 15,000= 135,000
400	100	2.5	1,000 "	480,000+ 60,000= 540,000
400	100	1.25	1,000 "	960,000+120,000=1,080,000

In each case one-quarter of the circular mils of the outer wire were taken as the size of the neutral, and one-half added to give the final figures in the last column. Considering the fact that 400 lamps can be lit, it will be readily perceived that the increase in copper is not great enough to make the difference in wire sizes a matter of much consequence. The system in use for direct and for alternating current is illustrated with respect to the generator connec-

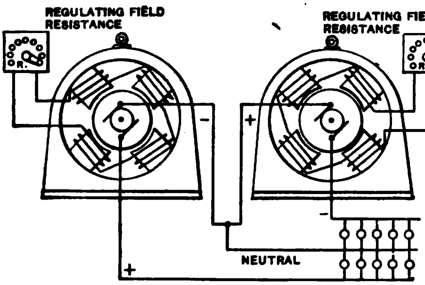


FIG. 20.—The Three-wire System with Generator Field Regulation—Direct Current.

tions in one case (Fig. 20) and the transformer connections (Fig. 21) in the other.

The Power Factor.—In single-phase systems, or, in fact, any system using an alternating current, the energy sent in does not necessarily appear in its full value. The illustrations showing the three-wire direct- and alternating-current systems differ in this respect: that in direct current the total watts are equal to the product of the volts and amperes, while in the alternating current the watts are equal to the volts × amperes multiplied by a determining power factor. The fact that the circuit may develop inductive action, and thereby accentuate the conditions through which the volts and amperes do not entirely co-operate, has been the reason why it must be considered. It is the cosine of an angle, or a measure

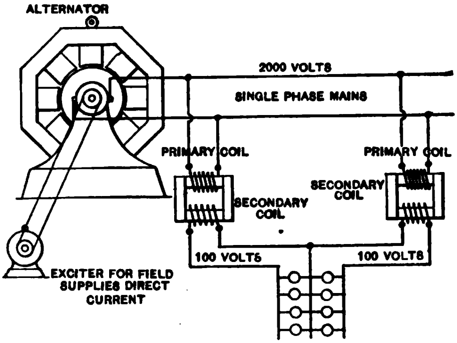


FIG 21.—The Three-wire System with Single-phase Current and Two Transformers Connected for Three-wire Lighting.

of the degree to which the co-operation is lacking between the volts and amperes. Its importance in power calculations confined to alternating currents is such that they are not comprehensible unless defined according to the limits it imposes. The following explanations will clear the way for conclusions relating to the elements of pressure, current, and the extent to which they co-operate.

Angle of Lag.—That which is called self-induction causes the current to lag behind the electromotive force. By this is meant that, although the electromotive force of the current passing into the circuit is operating upon the said circuit, it cannot instantaneously cause a current to flow. An interval of time elapses which is greater or less, according to the degree to which the effect of self-induction exercises its influence. The meaning of self-induction, as a physical fact, apart from the symbol L by which it is generally represented, is obtained by a consideration of the fact that lines of force surround the circuit or leave it when a current enters or leaves.

Self-induction.—The self-induction developed in the circuit is therefore measurable by the lines of force embracing it, and the time they take to either surround or leave it. In certain respects, when a current of electricity flows through a circuit, it is equivalent to that circuit being plunged into a magnetic field in such a manner as to produce electromotive force. The fact that the entering current is temporarily checked is due to the opposing electromotive force of self-induction. The conditions are similar to those which appear when a wheel (Fig. 22) is set into motion and then stopped. Inertia must be overcome to start the wheel, and it must also be overcome to stop the wheel. So in the same sense every electric current develops an electrical inertia to the entering current, and likewise develops an electrical inertia when the current reaches its exit. Though called self-induction, it is quite evident that the entering current must meet and overcome an opposing or counter electromotive force. It is also evident that a retreating current cannot be checked instantaneously. These two phenomena are characteristic of all currents, and may be illustrated as described, by reference to a fly wheel started and stopped, in com-

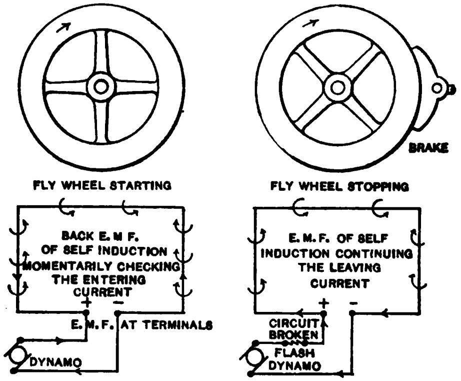


FIG. 22.—Simile of the Inertia Overcome in Starting and Stopping a Fly wheel to an Electric Circuit in which the Current is Sent in or Cut Off.

parison with a circuit being embraced and disengaged by lines of force.

Lines of Force Surrounding a Circuit.—As long as lines of force are increasing around a circuit, the circuit will continue to develop E.M.F., but when the circuit is broken, or the current stopped, the lines of force are disengaged. This phenomenon is accompanied by the development of another E.M.F. In other words, to make this fact more evident, when the current is entering the circuit the opposing E.M.F. of self-induction lets the current in only in a gradual manner comparatively. While only a fraction of a second elapses altogether, the reaction of the circuit takes time to subside, and in subsiding permits the E.M.F. trying to send a current through to perform its office. Thus the lag of the current behind the E.M.F. is an element of time though mathematically represented as an angle. The angle is readily explained by reference to a two-pole dynamo, or the two adjacent poles of an alternator.

Meaning of Angle of Lag.—In a two-pole dynamo the circumference represents 360 degrees. A conductor will pass through 180 degrees in passing each pole and one-half of the interpolar space between the pole pieces. If an alternating current is generated by this machine, then the conductor generating E.M.F. will have moved a slight distance before the current in the armature circuit responds. This interval of time corresponds to the angle through which the conductor moves. In the two adjacent poles of an alternator the same condition of affairs exists, except that the arc embraced by the two poles is given a valuation of 360 degrees.

The angle of lag is therefore a period of time which elapses before the current flows, and is represented by an angle forming a distinct percentage of the assumed 360 degrees subtended by the pole pieces. For instance, if the alternator is four-poled (Fig. 23), then a pair of poles, representing on this basis 360 degrees, would actually subtend only 180 degrees. A six-pole alternator would mean only 120 degrees for two adjacent poles; but, according to this standard, they would also represent 360 degrees from the beginning of the E.M.F. wave to the end of its complete reversal. This idea is represented in a series of alternators of 4, 6, and 8 poles with special reference to the angle of lag. The conditions would imply an

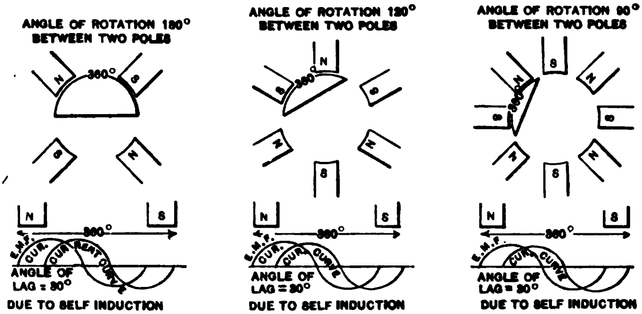

ANGLE OF ROTATION 180° BETWEEN TWO POLES
ANGLE OF ROTATION 120° BETWEEN TWO POLES
ANGLE OF ROTATION 90° BETWEEN TWO POLES
N
S
360°
E.M.F.
CUR.
CURRENT CURVE
CUR. CURVE
ANGLE OF LAG = 30°
DUE TO SELF INDUCTION

FIG. 23.—Angle of Lag Related to the 360 Degrees, by which Each Pair of Adjacent Poles are Represented, When an Alternating E.M.F. and Current are Generated.

equal amount of self-induction in each case, so that the angle of lag is equal throughout. In such a case, although the angle of rotation varies in the case of a 4-, 6-, or 8-pole machine, the angle of lag does not vary if the peripheral speeds are alike.

CHAPTER IV

SELF-INDUCTION AND RESISTANCE.—SELF-INDUCTION OF A COIL.—CAPACITY REACTANCE.—IMPEDANCE.—LIGHT AND POWER PROBLEMS.—RESONANCE IN CIRCUITS.—THE TRANSFORMER.—SINGLE-PHASE CURRENT POWER.—POWER-CURVES.—WHEN THE POWER-FACTOR IS ZERO.—EXAMPLES OF LAG.

Self-induction and Resistance.—When the current is suddenly varied in a circuit, the lines of force surrounding the circuit vary correspondingly, and create within it self-induction. But this self-induction is able to produce an effect within the circuit equivalent to the presence of resistance, as far as the limitation of the flow of current is concerned with an alternating electromotive force. The name given to this effect has been variously styled spurious resistance, inductive resistance, or reactance. It must be understood that the success of electric lighting and power distribution, as well as transmission, is dependent upon a proper consideration of the relationship existing between the self-induction, resistance, and capacity of the circuits carrying alternating electrical energy. By this is meant that the degree to which the angle of lag appears is a measure of the amount of useful power in the circuit. This inductive resistance arising in the circuit, through the variations in the current strength, is not an energy-wasting form of resistance. It simply suppresses the full manifestation of energy otherwise possible. The ohmic equivalent of it may be given by means of a simple calculation, p × L, which takes into consideration the frequency with which the current alternates per second, and the self-induction. The exact values of these are given under the symbols of $p = 2 \times \pi \times f$ and $L =$ henries, in which $f =$ cycles per second, $\pi = 3.1416$, and L represents a definite quantity obtained by special calculation. Before L is calculated in detail, with respect to coils carrying a current, the value of reactance, as it is called, when caused by self-induction and frequency, will be shown in a specific case. The inductive reactance of a coil, for instance, in which a current passes, alternating 100 times a second, and having a self-induction $L = .25$ henry, would be $2 \times \pi \times 100 \times .25 = 2 \times 3.1416 \times 100 \times .25 = 157.08$, representing the equivalent in ohms (Fig. 24) in the circuit. If the frequency were doubled the inductance reactance would be twice as much, or $2 \times 157.08 = 314.16$.

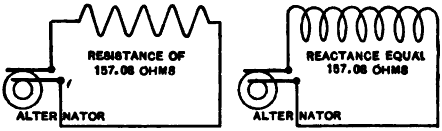


FIG. 24.—Resistance Equivalent of Inductive Reactance.

TABLE BASED UPON THE INDUCTIVE REACTANCE $2 \pi f L$.

Frequency.	Self-induction.	$2 \pi f L$.	Ohms equivalent.
10	.1 henry	6.28×10×.1	6.28
20	.1 "	6.28×20×.1	12.56
30	.1 "	6.28×30×.1	18.84
40	.1 "	6.28×40×.1	25.12
50	.1 "	6.28×50×.1	31.40
60	.1 "	6.28×60×.1	37.68
70	.1 "	6.28×70×.1	43.96
80	.1 "	6.28×80×.1	50.24
90	.1 "	6.28×90×.1	56.52
100	.1 "	6.28×100×.1	62.83

The above table shows the variations in reactance with systematic variations in the frequency. The ohmic equivalent of reactance, due to inductance, is thus shown to be increased if the frequency increases, and to decrease if the frequency decreases. The case above noted would be practically that of a coil of fixed self-induction, through which currents of an increasing frequency have passed.

Self-induction of a Coil.—The calculation of the self-induction of a coil is simple enough to only require arithmetical treatment. The elements to be considered are those relating to the construction and core of any coil. When the coil has or has not iron in it as a core (Fig. 25), the self-induction is less or greater in proportion to the permeability of the iron. The self-induction $L = 4 \pi^2 r^2 n^2 \div l \times 10^9$ when the coil is not very thick and contains no iron. If there is an iron core, then $L = 4 \pi^2 r^2 n^2 \mu \div l \times 10^9$, which is approximately true for the character of coils cited belonging to the class generally employed with fairly high frequencies on alternating current lines. In these two formulas, based upon the absolute system, L = henries of inductance, $\pi = 3.1416$, r = mean or average radius of coil in centimeters, n = the number of turns of wire, and l = length of coil in centimeters. The μ varies with the number of lines of force in the core or its degree of magnetization. In applying the formula the following case may be considered: A coil 20 centimeters long, whose average radius equals 10 centimeters, the number of turns being 500. According to the formula $L = 4 (3.1416)^2 \times 10^2 \times 500^2 \div 20 \times 10^9 = 4 \times 3.1416 \times 3.1416 \times 100 \times 250{,}000 \div 20 \times 10^9 = 3{,}948 \times 25 \times 10^4 \div 2 \times 10^{10}$ equals, after cancelling through, the total of .04935, or, what is called on the basis of $\frac{1}{1000}$ of a henry, being called a millihenry, 50 millihenries. These results may be developed with respect to a coil having iron in it, as mentioned with reference to the permeability μ. If in the case just noted the permeability is given as 500, then the result obtained,

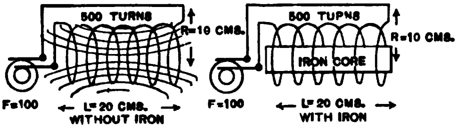


FIG. 25.—Comparison of Inductance of Coil With and Without Iron.

.04935 henries, will be multiplied by 500 and become 500 × .04935 = 24.675 henries. A table built up on this basis, showing the difference between a coil, with and without iron as a core, is given as follows:

TABLE SHOWING THE INDUCTANCE WITH AND WITHOUT IRON AS A CORE.

Iron.	Permeability.	Turns.	Length in cms.	Radius in cms.	Inductance.
None . . .	1	500	20	10	.04935
With	500	500	20	10	24.675

But another feature worth noting is that of the effect of the increase or decrease of the turns upon the inductance resulting. For instance, it is readily proven that the inductance varies as the square of the turns. In other words, if the turns are doubled (Fig. 26), the inductance becomes four times as great, as indicated in the following relative table of differences:

Turns.	Inductance.
1	1
2	4
3	9
4	16
5	25

The exact calculations would show the same result, based upon the fact that the turns are squared in the formula to get L. For instance, in the case given—that of a coil of 500 turns without iron as a core—when the turns are doubled, the inductance ought to be four times as great as .04935, or $4 \times .04935 = .19740$. Calculating with 1,000 turns, instead of 500, gives the following value: $L = 4 \pi^2 r^2 n^2 \div l \times 10^9 = 39.48 \times 100 \times 1{,}000{,}000 \div 20 \times 10^9 = 39.48 \times 10^8 \div 2 \times 10^{10} = 19.74 \div 100 = .1974$. This verification can be readily carried out in any other case, thus developing a principle of importance in an industry utilizing variable currents in inductive circuits. *Principle*—The self-induction is proportional to the square of the turns. A further verification could be made by making the turns three times as great, or 1,500, and noting that the inductance resulting would be nine times as great. The coil of 500 turns, with a mean radius of 5 centimeters and a length of 20 centimeters, when used as a basis, can become the foundation of a table in which the turns increase systematically. But it is evident that such a table would have to take into consideration the change in inductance, due to the change in the radius of the coil and perhaps in the length as well. But

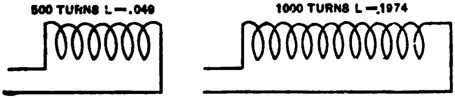


FIG. 26.—Doubling the Turns Gives Four Times the Inductance.

with this demonstration of the fact that self-induction can be calculated from the dimensions and conditions of a circuit, it becomes possible to refer to the reactance of a circuit due to its capacity.

Capacity Reactance.—Instead of the capacity in a circuit acting to hold the current back, its effect is just the opposite; it makes the current lead. A condenser of sufficient microfarads capacity, when connected to an alternating source of electricity, brings into existence a new phenomenon, namely, that of the current entering the circuit in advance of the pressure. The reason for this is found in the electrostatic qualities of the condenser itself. It really represents greatly extended terminals of an alternating-current circuit; as if the terminals were acting by electrostatic induction to obtain a charge: Being the circuit terminals in a sense, the condenser plates receive their electricity before the potential has reached its maximum value. The effect on a time basis is that of a charge in the condenser before the electromotive force has arrived. This presents the phenomenon of lead instead of lag, as is the case with the impeding effects of inductance. In ohmic equiv-

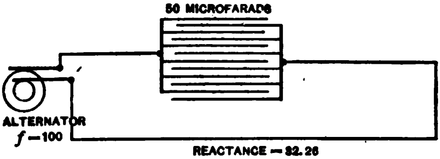


FIG. 27.—Capacity Reactance in a Circuit.

alents the reactance of capacity may be found by means of the following formula: Capacity reactance $= 1 \div 2 \pi$ f K, where $\pi = 3.1416$, f = frequency in cycles per second, and K = capacity in farads of the system. For instance, if a circuit has a capacity of .000050 of a farad, equal to 50 microfarads (Fig. 27), as ordinarily termed, and the current circulates back and forth at the rate of 100 times a second, the reactance valued in ohms would be $1 \div 2 \times 3.1416 \times 100 \times .000050 = 1 \div 628.32 \times .000050 = 1 \div .031 = 32.26$. The idea presented here is to show that the reactance due to the capacity and frequency, as well as the reactance due to inductance and frequency, represent tangible values. This is important with reference to the considerations involved in the total effect of resistance, self-induction, and capacity. This combination effect, as it may be called, is given the name of impedance.

Impedance.—All power-transmission circuits are estimated with reference to the impedance. The impedance may be called the combination of reactance and resistance. It is generally expressed in the following form: Impedance =

$$\sqrt{\text{Resistance}^2 + (\text{Reactance})^2}.$$

But it is well known that the forms of reactance are due to inductance and capacity, whose net effects upon each other are such that where related in a certain manner they neutralize each other. For instance, if impedance is to be properly estimated, the formula must be written in such a manner that cognizance is taken of this fact. Impedance, therefore, would be

$$\sqrt{\text{Resistance}^2 + (\text{inductance reactance} - \text{capacity reactance})^2}$$

in its exact form and value. Where the inductance predominates to such an extent that the capacity may be neglected, the formula for impedance becomes

$$\sqrt{R^2 + p^2\,L^2}.$$

But if the capacity reactance is sufficiently large to require valuation, then the impedance becomes

$$\sqrt{R^2 + (p\,L - \frac{1}{p\,K})^2}.$$

This merely represents an instance of where the capacity reactance is subtracted from the inductance reactance to get the correct impedance. The previous cases could be used as examples, but the following will also serve to illustrate the principle involved. If the resistance in ohms in a circuit is 10, and the inductance reactance 300, then, with a

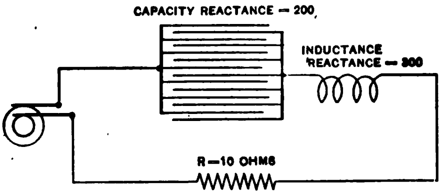


FIG. 28.—Impedance Due to Resistance, Self-induction, and Capacity.

capacity reactance of 200 (Fig. 28), the impedance would equal the

$$\sqrt{10^2+(300-200)^2}=\sqrt{10,100}=100+$$

The resistance effect in this case is almost negligible, for the reason that the reactance operating when squared gives 10,000; whereas the resistance of 10 only gives 100 when squared. An instance of this kind is one in which the resistance plays very little part in the transmission of power. As an example, the following may be given as a case where inductance is the chief factor. A 2,000-volt line has a resistance of 5 ohms (Fig. 29), and carries a current of 100 cycles a second with an inductance of 2 henries. The impedance, therefore, is the square root of $5^2 + (2 \times 3.1416 \times 100 \times 2)^2 = 25 + 1,579,144$; which clearly shows how negligible a quantity the line resistance becomes when much inductance is present. The reactance is practically the entire impedance representing the figures 1,256 in ohmic equivalents. On this basis the current in the line would equal 2,000 volts ÷ 1,256, or practically only 2 amperes. The new formula thus appearing for use

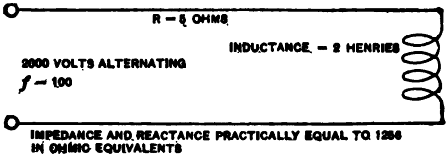

R = 5 OHMS
INDUCTANCE = 2 HENRIES
2000 VOLTS ALTERNATING
$f = 100$
IMPEDANCE AND REACTANCE PRACTICALLY EQUAL TO 1256 IN OHMIC EQUIVALENTS

FIG. 29.—When Resistance is Low it is Negligible Compared to the Reactance.

in connection with this state of affairs would be $C = E \div \sqrt{R^2 + p^2 L^2}$ for the value of the amperes.

Light and Power Problems.—The light and power problems are those which consider efficient power delivery as well as efficient light production. The neglect of circuit conditions is no worse than the disregard of the best means of producing light.

For instance, the expenditure of 1,000 watts for lighting really means the expenditure of more, because of the losses in distribution. It is difficult to grasp the nature of many of these problems, unless the effort is made with the backing of a certain amount of technical knowledge. For this reason the *résumé* preceding these remarks has been made with the intent of presenting certain facts bearing upon the average case. No lines can be strung any great distance, or buried underground, which do not represent cases of the presence of inductance and capacity. The degree to which each are present is largely a matter of the make-up or configuration of the system. Capacity is dependent upon the nearness of one conductor to another, as well as the nature of the dielectric used as insulation. Inductance is dependent upon the number of interlinkings taking place between the conductors respectively and the lines of force. It is thus evident, in the consideration of the conditions existing in light, heat, and power installations, that a knowledge of the values of inductance reactance, and capacity reactance, is absolutely essential if a true insight into circuit conditions is desired.

Unless this is found the impedance will not be known at its true value. The current that is to be sent through a circuit will be impeded unduly, and the entire volume of power delivered is apt to be far below the value anticipated. In systems of power transmission and distribution the line losses are generally estimated at a certain percentage of the whole power. The design of the conductor to meet these conditions is, therefore, imperative, if intelligently pursued along the lines indicated.

Resonance in Circuits.—By resonance in circuits is meant a condition in virtue of which neither the capacity or inductive reactance is individually operative. While both are present, yet neither appears except as a cause for a high internal electromotive force. The circuit in which both these influences exist then acts as though there were only resistance present. The condition is expressed by the statement that the impedance due to inductive and capacity reactance is zero. For instance, if the resistance of a circuit carrying an alternating current were 10 ohms, and the capacity and inductive reactance equal respectively to 50 apiece, then, according to the formula, the impedance equals the square root of $10^2 + (50 - 50)^2$, which equals 10. In this case the formula for impedance has been closely followed and values given to the indicated symbols. The formula is expressed as follows: Impedance =

$$\sqrt{R^2 + (p\,L - \frac{1}{p\,K})^2}$$

in which $R =$ ohms, $p = 2\pi f$ where $f =$ frequency, $L =$ inductance, and $K =$ capacity in farads. The fact that, in the example given, p L was made equal to 1 ÷ p K, means that the inductive and capacity resistance when made equal create a condition within the circuit the same as though only ohmic resistance were present. For this reason a circuit is in a resonant condition when the obliteration of each particular effect is complete enough to leave only room for the purely ohmic effect. When a circuit has a resistance of 10 ohms, and an inductive and capacity reactance respectively of 50 ohms equivalent, then the

$$\sqrt{10^2+(50-50)^2}$$

is evidently equal to only 10. But although only a 10-ohm resistance actually remains, the inductance within the coil is capable of developing a very high electromotive force. If, for instance, 100 volts are applied, then 100 ÷ 10 = 10 amperes in the coil; but the reactance due to self-induction is 50 (Fig. 30), therefore the E.M.F. of inductance will equal 10 × 50 = 500 volts.

This represents the degree of reaction due to the inductance or inductive reactance multiplied by the current. The presentation of these facts is made for the purpose of showing how power and lighting circuits are affected by inductive and capacity reactances. To recapitulate, lead is caused by capacity operating in a circuit to a great enough extent to hurry the current forward; lag is caused by inductance operating in a circuit to a great enough extent to retard the progress of the current.

The technical form of expression given is that the capacity causes the current to lead the impressed E.M.F.; also that self-induction causes the current to lag behind the impressed E.M.F. The effect of the resistance itself is to cause both the current and E.M.F. to be in perfect phase with each other. In other words, if an electric circuit was not affected by capacity or inductance, if neither were present, the current would not lead or lag, but be in phase with the impressed E.M.F.

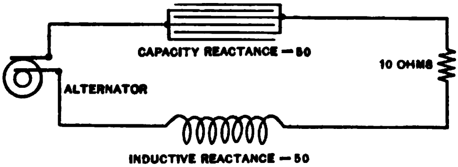


FIG. 30.—Circuit in which Capacity and Inductive Reactance are Equal, Making it Resonant. Only Resistance Remains.

The Transformer.—Alternating currents are successfully handled in connection with electric-light and power work by means of transformers or converters. There are two general classifications to be made of this particular form of apparatus. First, the ordinary type of transformer, by means of which an alternating current of high potential (Fig. 31) can be converted into one of low potential, or *vice versa.* Second, the class of machines termed rotary converters, by means of which an alternating current can be transformed into a direct current, or *vice versa.* By means of both types of devices, alternating and direct current can be moulded to suit the wishes of the engineering experts intrusted with the design and development of any such propositions. It is needless to add that both the transformer and the rotary converter are closely associated together in the work of transmitting and distributing electricity for light and power purposes. The method of combining them is seen in the illustration, which shows how an alternating current is handled from the source of its generation to the point or points of distribution. The various processes involved may be noted in the following synopsis:

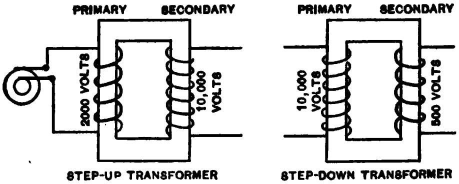


FIG. 31.—Transformers for Raising and Lowering Voltage.

First—The hydraulic or mechanical energy obtained from water-power or the burning of coal, oil, or wood is utilized to produce rotation.

Second—The electrical generators are connected up for the purpose of transforming the mechanical energy of rotation into two- or three-phase alternating of a pressure varying from 500 to 2,000 volts or over, as the case may be.

Third—The alternating current thus generated is sent into one or more step-up transformers, whose function it is to raise the potential, without any considerable loss of energy, to an economic value for efficient transmission.

Fourth—The high-tension alternating of from 5,000 to 6,000 volts is transmitted over the power-lines to a point at which the first step toward distribution takes place in lowering the potential.

Fifth—The station or stations receiving the high-tension alternating current convert it in one or more step-down transformers to a lower pressure while retaining a reasonably high efficiency in the process.

Sixth—The electricity is then transmitted to one or more rotary converters, which transform the alternating into a direct current (Fig. 32) ready for distribution. The low-pressure alternating can be distributed at once for power and light purposes, but it is the usual practice, where trolley systems are to be operated, to convert the alternating into 500 or 600 volts direct. The forms of energy in-

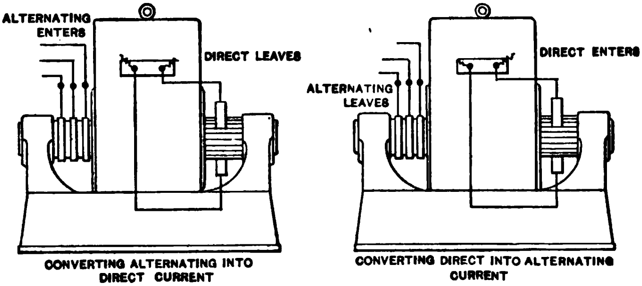

ALTERNATING ENTERS
DIRECT LEAVES
CONVERTING ALTERNATING INTO DIRECT CURRENT
DIRECT ENTERS
ALTERNATING LEAVES
CONVERTING DIRECT INTO ALTERNATING CURRENT

FIG. 32.—Rotary Converters.

volved in this complicated process are as follows: First, medium-pressure alternating; second, high-pressure alternating; third, low-pressure alternating; fourth, low-pressure direct current. As each of these transformations involve the use of a device whose efficient operation determines the power returned from the process, it is evident that the character of the process itself must be ultimately examined to grasp the limitations of the efficiency involved.

Single-phase Current Power.—The amount of power produced by a single-phase current is best known by reference to the power factor. The greater or less this is the greater or less the single-phase power in the circuit. The plotting of the E.M.F. and current as two sine waves, with the difference of phase showing between them, does not convey in an adequate manner the amount of power involved. Calculations taking into consideration the power factor will do so, as, for instance, if the power factor is 80, 90, or 95, and the volts 100 and the amperes 10 or a product of 1,000, then with these power factors the total power in each case would be 800, 900, and 950 watts respectively. But this condition can be represented by means of a curve showing the conjunctive action of the E.M.F. and current in each and every case of this character arising.

Power Curves.—What are called power curves are simply illustrations of the principle, simple in itself, of multiplying together the volts and amperes of power to obtain a new curve (Fig. 33) embodying this product. The sine wave of the volts consists of a curve due to a variety of values of E.M.F. Each point on the curve is represented by a vertical line called the ordinate. The termination of this line is the point of the curve, and an immense number of values between one zero and another gives the curve itself. The volts are therefore an instance of a rise of E.M.F. from zero to a maximum called the amplitude, and a comparatively gradual drop to zero again. The same is true of the curve of the current. It has its two zero values where it begins and ends, and its amplitude as well. If the two ordinates at any given point, or at all points of the curves, are multiplied together, it is evident that where only one ordinate is found, and the other is missing, there is no power. The same is true where the zero points are found on both curves. The fact must also be considered that the power curve thus drawn will be

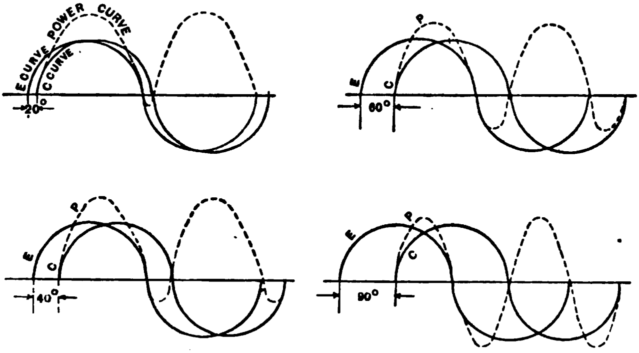


FIG. 33.—Power-curves Below the Zero-line as the Angle of Lag Increases, until at 90 Degrees Curves Above and Below are Equal.

partly above and partly below the locus or zero line. The only exception will be found when there is no difference of phase between the E.M.F. and current. This condition will be considered in connection with those cases arising where the phase difference exists. Examination of the curves of E.M.F. and current, showing a lag of the current behind the E.M.F., indicates a series of zero values for both the E.M.F. and current. The first zero value is found where the E.M.F. begins. The second zero value is found where the current curve begins. The third zero value is found where the E.M.F. curve ends preparatory to the beginning of a new curve on the under side of the zero line. The fourth zero is found where the current curve crosses the zero line after becoming zero, and about to begin a new curve on the under side of the zero line. The fifth zero is found where the E.M.F. curve on the under side of the zero line returns to the zero line and to zero. The sixth zero is found where the current curve on the under side of the zero line returns again to the zero line and to zero. The six zero points will always appear when there is a lag between the E.M.F. and current. They are significant because they represent the six zero points of the power curve constructed by multiplying the E.M.F. and current ordinates together. Wherever a zero point appears it is evident there can be no power, however large the ordinates of the other element of power. For this reason the curve of power will rise above the zero line where there are only positive ordinates to be multiplied together, and it will fall below the zero line wherever there are positive and negative ordinates to be multiplied together. But it must be remembered that it will also rise above the zero line whenever *negative* elements are multiplied by *negative* elements. The zero line, it may be known, with reference to this state of affairs, indicates also the difference between the power consumed and the power returned. For instance, the extent to which the power line dips below the zero line is a measure of the amount of negative power or power returned to the generators. The extent to which the power line appears above the zero line is a measure of the amount of positive or available power that is or can be utilized. When the ordinates of the E.M.F. and current are therefore multiplied together, the power curve will be found to rise above the zero line and fall below it, forming a curve of four amplitudes when lag exists. As the lag increases or diminishes, the power curve appears more below the line or above it. With great lag, it is more below the line. With less lag, it is more above the line. When the lag equals 90 degrees, it is as much above the line as below it. In other words, there is as much power returned to the generator as it sends out. Illustrations of these cases are given for the purpose of showing the ebb and flow of the energy, both when such ebb and flow is useful and when it is useless.

When the Power Factor is Zero.—When the power factor is zero, it means that the angle of lag equals 90 degrees between the current and E.M.F. In this case the cosine of this angle equals zero, and the multiplication of the current and E.M.F. elements, however large, when again multiplied by the power factor zero would give only zero. But this does not mean an absence of electrical energy in the circuit; its elements are there, but not in an available form. Therefore the false power pulsates in and out of the circuit without accomplishing anything. The fact that the power wave is equal above and below the line clearly indicates this pumping out and withdrawal of the electrical energy from the generator into the circuit and back again. An alternator producing a current with a 90-degree lag is therefore only consuming enough energy to run as an idle machine. Friction and certain iron losses are the only ones met with. To make it consume more power, it must establish a current in a circuit in which the lag is less than 90 degrees.

Examples of Lag.—Practical examples of lag may be given and illustrated, to show the ideas contained in this exposition of its meaning with respect to the total power. One or more incandescent lamps may be connected in multiple, with a coil inserted in one lag of the line. The current is alternating, and the coil of such a low resistance that the candle-power of the lamp is not affected. The coil must be so wound that it will receive a core of divided iron of a high quality. The following series of experiments may then be tried: First, the lamp and coil in series will cause no change in the candle-power of the lamp. Second, a core of iron inserted a very short distance within the coil will cause a perceptible lowering of the candle-power of the lamp. Third, the insertion of the core about one-third or one-half the distance will cause the lamp to drop in candle-power to a bright red. Fourth, the total insertion of the core (Fig. 34) will serve to put the lamp practically out. The explanation given is two-fold and as follows: The coil, in the first place, has very little inductance reactance, because the effects of self-inductance are not very marked. The permeability μ is only equal to 1, and the inductance in consequence limited. But with the introduction of an iron core the number of lines of force increase, the self-induction increases, and the lag and impedance also increase. This is made manifest by the drop in candle-power to a point where no light appears, because the energy has been almost entirely choked. This idea is of great value in forming a proper estimate of the reactions occurring in the primary and secondary coils of a transformer.

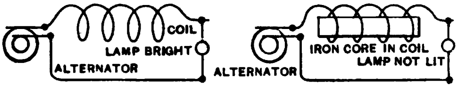


FIG. 34.—Effect of Inductance of the Light of a Lamp.

The regulation effected by which a uniform candle-power is preserved in the lighting circuits depends upon the crystallization of such principles.

CHAPTER V

THE TRANSFORMER FOR LIGHT AND POWER.—MUTUAL INDUCTION.—LOSSES OF POWER.—RATIO OF PRESSURES.—WITHOUT LOAD.—WITH LOAD.—RELATIONSHIP OF PRIMARY AND SECONDARY CURRENT.—CALCULATING THE E.M.F. OF THE COILS. — IRON LOSSES.—MUTUAL- AND SELF-INDUCTION.—THE TRANSFORMER IRON.—THE PERMEABILITY OF THE IRON.—CALCULATION OF HYSTERESIS OF IRON.—PERMEABILITY AND COERCIVE FORCE.—FORMULA FOR HYSTERESIS.—CHOICE OF IRON.—CURVE OF HYSTERESIS LOSS.—PRINCIPLES OF DESIGN.

The Transformer for Light and Power.—The use of the transformer for light and power has been the means of making the alternating-current system highly elastic in character. The value of the transformer as an efficient machine depends upon the extent to which it can meet the following requirements:

First—At no load the primary winding carries little or practically no current, and therefore the waste of energy is very limited when the transformer is not in use.

Second—That the losses in the iron of the transformer, due to eddy currents, are very small at all conditions of load.

Third—That the losses in the iron of the transformer, due to the effect of hysteresis, are limited so as to be within the bounds of a high efficiency at all points of load on the secondary.

Fourth—That the resistance of both primary and secondary windings is such that the heat loss (Fig. 35) is not excessive at either full load or no load.

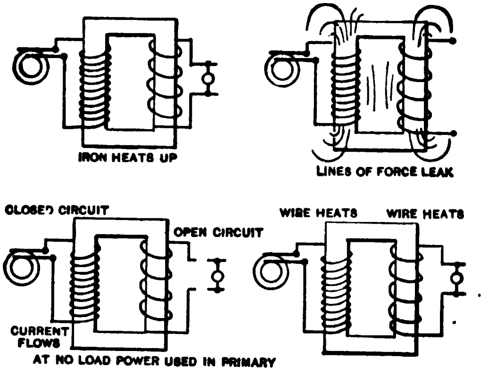


FIG. 35.—Sources of Wasted Power in a Transformer.

Fifth—That there is no magnetic leakage between the poles of the coils, thus causing the lines of force that should enter the cores to pass on the outside.

Sixth—That at no load the impressed E.M.F. of the primary and the back E.M.F. of self-induction are sufficiently equivalent to prevent all but a minimum of current from passing through.

To properly review the influence of the transformer upon electric-light and power work it is necessary to form a correct estimate of the extent to which each of its essential elements contributes to the net result. From a general standpoint, it may be said that the transformer merely consists of two coils —one called a primary and the other a secondary— wound upon a core of divided or laminated iron. The primary coil is connected to a source of impressed E.M.F., as it is called. The secondary is connected to the lighting or power circuit, as the case may be.

Mutual Induction.—The effect of one coil upon the other is due to mutual induction. The adjustment of the power entering the primary, so as to affect the secondary, is accomplished by the natural regulative effect of the self-induction in the primary.

It may be stated, therefore, without equivocation, that the actual development of power in the totally disassociated secondary is due to the direct effect of mutual induction. On the other hand, the regulation of the power in the primary coil, through which power adjustments take place, not only in it, but in

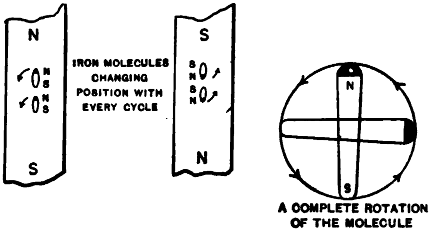

N
S
IRON MOLECULES CHANGING POSITION WITH EVERY CYCLE
S
N
N
S
A COMPLETE ROTATION OF THE MOLECULE

FIG. 36.—Rotation of an Iron Molecule During Magnetization and Reversed Magnetization.

all parts of the connected system, is due to the self-induction.

Losses of Power.—The exact source of losses of power in the transformer may be summed up in the following list: First, losses in pressure in both primary and secondary, due to the natural or ohmic resistance of the wire; second, losses of power in watts arising through the development of heat in the said coils, and commonly called the C^2R loss; third, losses in the iron (Fig. 36), which are due to two distinct causes: First, the development of minute parasitical currents in the iron itself, which consume energy called eddy currents (Fig. 37); and, second, to the effect of hysteresis, caused by the constant reversals of magnetism; all of which combine to raise the temperature of the iron. Thus, influences will be at work to heat the coils, unless provision is made to hold them in check. And, in addition, other

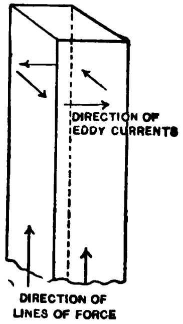


FIG. 37.—An Enlarged Iron Sheet, Showing Eddy Currents.

influences are at work to heat the iron, which must be similarly understood and held in check. The alternator generating the current now employed so widely is not one whit more important than the transformer, whose function is that of raising or lowering its pressure. A very efficient alternator delivering, say, 100 kw. to the transformer or transformers in its circuit may not lose more than 10 per cent of its energy in the entire process of generation and distribution. Of the 100 kw., about 90 kw. will be on tap for consumers' use whenever required.

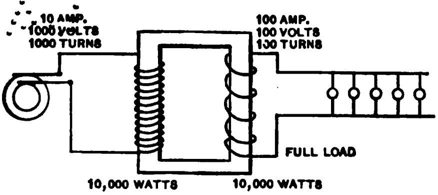


FIG. 38.—Ratio of Windings, Volts, and Current in a Transformer.

Ratio of Pressures.—The two pressures of the transformers are called the primary electromotive force and the secondary electromotive force. The exact ratio of these two pressures is the exact ratio of their windings in theory and practice. For instance, if 1,000 turns on the primary (Fig. 38) take 1,000 volts, then 100 volts from the secondary can be obtained by means of 100 turns. The ratio is, therefore, as follows: E.M.F. of primary; E.M.F. of secondary, as the turns of the primary are to the turns of the secondary. A simple rule of this character also presents the facts with respect to the current as well. For instance, if the number of watts in the primary are 10,000 and the current in the primary is 10 amperes, then, as 10,000 watts are practically delivered by the secondary, the current in amperes, at 100 volts pressure, would be 10 times as great, or 100. The rule therefore appears, relating to this, as follows: The current in the primary is to the current in the secondary as the pressure in the secondary is to the pressure in the primary. This is represented by the symbols in the following manner, both with regard to the pressures and windings, as well as the ratios of the currents: $E_p : E_s = S_p : S_s$ as regards the electromotive forces and primary and secondary windings; also $C_p : C_s = E_s : E_p$ as regards the currents and electromotive forces.

Without Load. — When there is no load, the secondary of the transformer is said to be on open circuit, and the current in the primary is at its lowest value. The electromotive force induced in the primary coil through self-induction is so high that only a small difference exists between it and the E.M.F. sent in from the alternator. This difference of E.M.F. is useful in keeping the primary coil choked as it were. Under these conditions, namely, of open circuit for the secondary (Fig. 39), the primary coil represents a simple case of a highly self-inductive coil in circuit with an alternating current. Its inductive reactance under these conditions is obviously at a maximum. The value of p L is therefore sufficiently high to prevent any but a very small current from operating. At this point the transformer represents a negligible consumption of power. Should it be otherwise, however, a case exists of where power is being unduly wasted as a consequence of bad design. If 100 transformers are considered, taking on an average of from .1 to .2 of an ampere apiece, the total power consumption at 2,000 volts would be 100 × .1 × 2,000, or 100 × .2 × 2,000, equal respectively to 20,000 or 40,000 watts. The design of a transformer, therefore, must be such that the waste of power at no load is extremely low, otherwise a power leak or waste will appear which may seriously affect the financial returns. The primaries of the transformers of an extensive system of electric lighting are regarded as costing a definite sum per annum for power losses. Inventions made for the purpose of automatically cutting out the primaries when the secondary circuits are opened have not proved practicable.

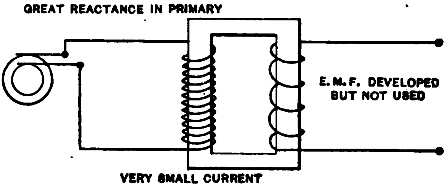


FIG. 39.—Inductive Reactance with Secondary Open.

With Load.—When the secondary of the transformer is closed, the amount of current flowing into the primary and secondary immediately becomes automatically regulated by inductive influences. Even though the secondary is open, the mutually inductive effect of the primary is such as to cause electromotive force to be generated in it. In other words, although no current flows in the secondary, it is in certain respects no different from the armature of a generator on open circuit. The field is actively operating, but the conductors of the armature, though generating E.M.F., cannot cause a current to flow until the circuit is closed. When this occurs in the case of the secondary, when it is being used to generate current for lighting or power purposes, the current flowing in it exercises a reverse magnetic influence (Fig. 40) to that in the primary. In fact, the effect is such that not only is the amount of magnetism in the transformer cut down, but the back E.M.F. of the primary is necessarily cut down, and, in consequence, the E.M.F. of the secondary as well. The case, as here presented, is that of the closing of the secondary, causing current to flow in that coil,

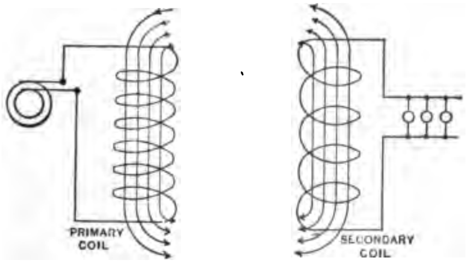


FIG. 40.—Opposing Magnetizations of Primary and Secondary.

thereby magnetizing its core in a reverse direction to that caused by the primary, thus cutting down the magnetization of the primary and permitting more current to enter it. The fact to be noted, however, is that a very slight difference between the E.M.F. impressed upon the terminals of the primary by the alternator and the E.M.F. induced within the coil of the primary through self-induction, will be quite sufficient to send a greatly increased current through the primary. Regulation here, in this respect, is very delicate, and it is evident that both the increased magnetization due to the increased ampere turns of the primary, and the increased but reverse magnetization due to the current in the secondary will very nearly balance. In other words, the magnetization of the primary and the demagnetization of the secondary will be approximately equal. Under these conditions the magnetization of the transformer iron, under all conditions of load, will remain practically unchanged.

Relationship of Primary and Secondary Current.—The current in the primary is controlled by the degree of mutual induction taking place between it and the current in the secondary. The coils are only the mediums through which they operate and affect each other. Their lines of force are the essential and fundamental basis of all reactions. The primary is therefore magnetically as much a part of the secondary as the secondary is a part of the primary. Each is mutually sensitive to changes taking place in the other. The current in the primary could not increase

(Fig. 41) unless the secondary by its reaction permitted it. It is evident that the only way in which the current in the primary can increase is by a reduction of the difference between its impressed and its back E.M.F. But to lower the back E.M.F. it is necessary to reduce the inductive reactance, a thing only possible by reducing the number of lines of force producing it. Under these circumstances, it is evident that the only efficient means to employ (were none other available) would be to reduce the number of lines of force as they are automatically reduced by the current in the secondary. When the secondary circuit is closed the amount of current flowing through it is dependent upon the amount of resistance in the outside circuit connected to it. For this reason, as more and more incandescent lamps are turned on in the secondary circuit of a transformer, the resistance is reduced more and more, and in consequence a heavier volume of current flows through the secondary coil. As more current flows through

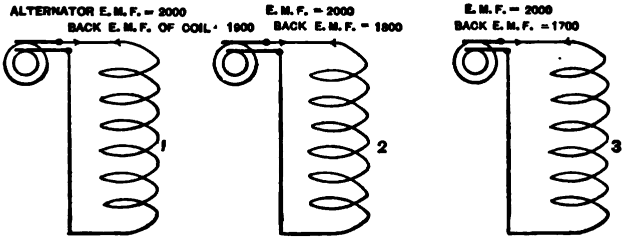


FIG. 41.—Relative Decrease in Back Electromotive Force of Primary Coil with Increase of Current in Secondary.

the secondary coil, its reverse magnetizing effect to that of the primary coil cuts down the total amount of lines of force to just the extent required to permit only enough extra current to flow in the primary to do the work required. In other words, when the primary gets more current it is because the secondary takes more current. On the other hand, when the primary takes less current it is because the secondary has reduced its quota of current by the turning off of lamp-circuits, etc. Both the iron and the copper in these specific cases are merely the mediums which carry the energy employed. In the one case the energy as current, and in the other case the energy as magnetism.

Calculating the E.M.F. of the Coils.—The two electromotive forces of the primary and secondary respectively can be calculated by means of a simple formula embracing the total number of lines of force, the total turns, and the frequency. The formula is as follows:

Total lines of force in core = volts $\times 10^8 \div 4.44 \times$ turns of wire $\times$ frequency.

For instance, in showing its application, if the volts required are 1,000, the frequency 100, and turns of wire 1,000, the formula would then represent: Total lines of force in core $= 1{,}000 \times 10^8 \div 4.44 \times 1{,}000 \times 100$ equals 225,225. The lines of force in the core would not be very high per square inch, for reasons that will be readily made obvious. The calculation of volts, lines of force, or turns is manifestly dependent upon the arrangement of the formula. To get turns, the formula is arranged as follows: Turns $= E \times 10^8 \div 4.44 \times$ total lines of force $\times$ frequency. To get volts, the formula reads: Volts $= 4.44 \times$ turns $\times$ maximum lines of force $\times$ frequency $\div 10^8$. In this formula the total lines of force are the maximum created by the current in the primary coil. The volts obtained by this means, however, are the effective volts. The maximum volts divided by the $\sqrt{2}$ equal the effective volts, or the volts read off from an alternating-current voltmeter. According to this last calculation, a 110-volt alternating-current lighting circuit is supplying an effective or commercial pressure of 110 volts, but a maximum pressure of

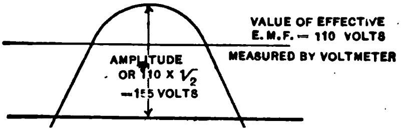


FIG. 42.—Difference Between the Commercial or Effective Pressure and the Maximum or Amplitude.

$$110 \times \sqrt{2} = 110 \times 1.41 = 155 \text{ volts.}$$

This is called the amplitude (Fig. 42) of the pressure, and is the highest point reached by the sine wave of electromotive force.

Iron Losses.—The reason why the magnetism in the core is not made high is because of the effects of hysteresis. By some this has been called molecular friction. But it is readily understood as the phenomenon causing energy to be absorbed during the process of magnetization and a reversal of magnetism. The greater the number of lines of force per cubic inch of iron in the transformer core, the greater the energy absorbed in the process referred to of reversing it. Therefore, the magnetization in transformers is limited to a certain safe maximum. Beyond this point a great waste of power and high temperature in the iron are inevitable. This is called the limit of the flux density.

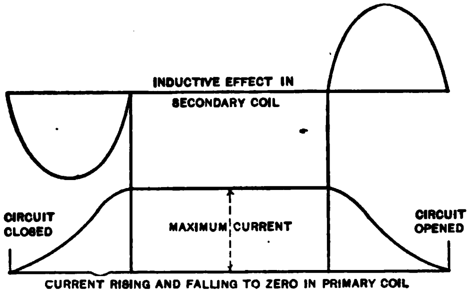

INDUCTIVE EFFECT IN SECONDARY COIL
CIRCUIT CLOSED
MAXIMUM CURRENT
CIRCUIT OPENED
CURRENT RISING AND FALLING TO ZERO IN PRIMARY COIL

FIG. 43.—Action of a Primary on a Secondary Coil

Mutual and Self-induction.—Both inductions are caused by the interlinking of lines of force with the turns of wire. The transformer is peculiarly representative of a case where mutual induction occurs between the primary and secondary coils, and self-induction in each coil individually. An illustration (Fig. 43) showing the self-inductive relationship in any coil when current is introduced, to the current due to the impressed E.M.F., will serve to emphasize the true meaning of this phenomenon. It is not essentially different when an alternating current is introduced, except in so far as it represents more complications, because of the rise and fall to zero of the current in one direction, and its rise and fall to zero in the opposite direction. The influence operating is always reactive. By this is meant that when the current attempts to grow in strength the reaction grows likewise. Whereas, on the other hand, when the current tends to decrease in strength, the reaction is reversed. It then strengthens the current as it tends to diminish, sustaining it beyond its normal time, and causing the flash or kick to appear when the circuit is broken.

The entire process is due to the effect of a variation in the lines of force when the current is either increasing or diminishing. In a transformer the inductance is three-fold in the sense that both self and mutual inductance occur in the two coils, as follows: 1st—Self-induction in the primary due to the increasing and diminishing current. 2d—Mutual induction between the primary and secondary. 3d—Self-induction in the secondary coil. The correct impression is best conveyed by the realization of the magnetic relationship between the coils when a core of iron of a continuous character permits the lines of force to freely operate upon both. The commercial value of the self-induction is found in its automatic regulation both of the energy entering the primary and the energy developing in the secondary. The mutual inductance between the primary and secondary is one henry when the number of lines of force from the primary coil due to one ampere which interlinks the secondary coil are equal to 100,000,000. Or this may be stated by saying that "the mutual inductance of two coils is one henry when the passage of one ampere through one coil causes a total magnetic flux of 10^8 lines of force to be linked with the secondary coil."

The Transformer Iron.—Losses of power in the iron represent the exact amount of power wasted

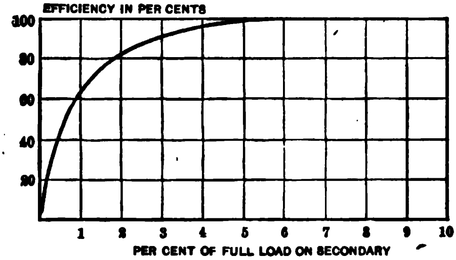


Fig. 44.—Efficiency Curve of a Transformer with Various Loads.

in eddy currents and hysteresis. Using a very high grade of soft iron of little coercive force will reduce the hysteresis, as this is entirely a molecular affair. But eddy currents are only reduced by laminating the iron—that is, using it in the form of thin sheets. The efficiency of a transformer (Fig. 44) is greatly dependent upon the character of its design in this respect. Such design is best obtained by the use of iron of the lowest coercive force and the highest permeability. For instance, if a transformer dissipates

500 watts out of 5,000, then the efficiency equals $4,500 \div 5,000 = 90$ per cent. But the 500 watts wasted may be regarded as consisting of the following:

Loss of power in watts in the iron core due to eddy currents and hysteresis	= 150
Loss of power in watts in the primary coil due to the C^2R effect	= 150
Loss of power in watts in the secondary coil due to the C^2R effect	= 200
Total loss of power in the transformer due to all energy-wasting causes	= 500

The Permeability of Iron.—The permeability of the iron employed is of such importance that an exact knowledge is required of the figures by which it is represented. In the table on page 114 the magnetizing force required and the permeability of sheet steel and annealed soft iron are given.

The act of magnetization is accompanied by certain phenomena, as noted in the following synopsis: 1st—The fact that with a small magnetizing force a comparatively large magnetic change takes place in the iron. This has been called by some authors the elastic stage. 2d—The fact that with a small additional force, when a certain point in magnetization is reached, a comparatively complete magnetization takes place. This has been called by Fleming the catastrophic stage. 3d—The fact that with a great increase in the magnetizing force a very limited response occurs magnetically in the iron. To reverse this operation necessarily represents the ab-

MAGNETIZATION DATA OF MILD ANNEALED STEEL AND SOFT SWEDISH IRON AT ABOUT 60 DEGREES FAHRENHEIT.

Lines of force per sq. cm.	Magnetizing force H required for		Permeability μ for	
	Annealed cast sheet steel.	Annealed soft iron.	Annealed cast sheet steel.	Annealed soft iron.
2,000	1.2	0.8	1,800	2,675
4,000	1.7	1.17	2,400	3,375
6,000	2.5	1.73	2,425	3,500
8,000	3.7	2.55	2,150	3,150
10,000	5.55	3.95	1,800	2,550
12,000	8.95	6.45	1,375	1,850
14,000	15.00	12.00	950	1,050
16,000	29.00	54.00	550	325
18,000	90.00	126.00	200	125
20,000	224.00	324.00	87	55

sorption of power. This power, it seems, disappears in the effort to return the iron to its normal condition, and then reappears as heat. The iron will, when heated, respond more readily to small magnetizing forces. Its permeability under this condition is increased. The entire action is that of the molecules of iron attracting each other so strongly that a certain amount of force is required, not only to break this attraction as it normally occurs and rearrange them, but it is also required to bring them back to where they started from.

Calculation of Hysteresis in Iron.—It is best to realize that the quality of iron best suited to alternating-current work is iron of such a character that its coercive force is least. In magnetizing a piece of iron, the process may be considered in the following manner: First, the iron is magnetized by means of a coil of wire carrying a current. Its magnetization under such circumstances mav be very high, in fact it may be saturated. The next step is to reduce and withdraw the current. When this is done the iron, if examined, will be found to be still magnetized. In order to reduce this magnetization to zero it will be necessary to use a certain amount of electrical energy in the reverse direction. It is quite evident that the greater the amount of energy required to accomplish this, the poorer the quality of iron is for transformer use. On the other hand, if the demagnetization of the iron is continued in the opposite direction until it reaches a point equally as high this way as the other, it is only to be expected that the same process must be followed out to bring it back to zero again. If, for instance, during the magnetization of the iron up to a certain point and its return to zero, 5 watts are consumed, then it would require 5 watts to reverse its magnetization up to the same point and back. The total during the entire operation would therefore be 5 + 5 = 10 watts loss. This complete operation is called a cycle of magnetization, and is due to the effect of a complete cycle of current in a coil upon a core of iron. If the cycles are 100 per second, the watts wasted in the iron would be 10 × 100 = 1,000 per second. It is readily seen that the further the magnetization is pushed the more difficult it is to reverse and complete the cycle without a comparatively great loss of power. But it is also evident that the quality of the iron, through which it absorbs energy, is the feature which regulates its value as to its use in transformer construction.

Permeability and Coercive Force.—The facts as thus presented mark the difference between the permeability of the iron and the degree to which it absorbs energy during magnetization and demagnetization. Although iron may have a very high permeability, it does not necessarily follow that the coercive force required is therefore very low. This important point is represented by means of a diagrammatic sketch (Fig. 45) in which the magnetiza-

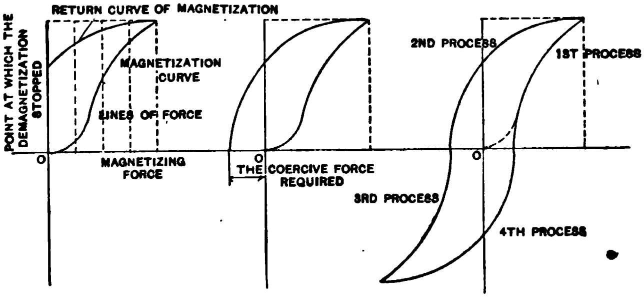

RETURN CURVE OF MAGNETIZATION
POINT AT WHICH THE DEMAGNETIZATION STOPPED
MAGNETIZATION CURVE
LINES OF FORCE
O
MAGNETIZING FORCE
O
THE COERCIVE FORCE REQUIRED
2ND PROCESS
1ST PROCESS
O
3RD PROCESS
4TH PROCESS

FIG. 45.

The Retentiveness of the Iron Illustrated.

Diagram Showing the Coercive Force Required to Bring the Iron Back to Zero.

The Processes Involved in a Complete Magnetic Cycle.

tion of a piece of iron is represented with the return curve showing the extent to which the iron returns to its neutral condition. The greater the distance between the return curve and the zero point, the more the likelihood exists of the iron absorbing energy. These ideas are presented in the form of a series of sketches which show the retentiveness of the iron, the degree of coerciveness in the iron, and the processes involved in a complete cycle of magnetization.

Formula for Hysteresis.—Steinmetz investigated the relationship existing between a certain grade of iron and the amount of energy it absorbs. The examination of a variety of kinds of iron clearly indicated that the energy was absorbed in strict proportion to certain elements which were best considered in the shape of a formula, as follows:

Hysteresis in ergs = a constant × (lines of force per sq. cm.)$^{1.6}$.

If the formula is represented symbolically the following values appear: $H =$ ergs, $B =$ lines of force per sq. cm., constant $= .002$, the formula then becomes: Hysteresis in ergs $= .002 \times B^{1.6}$. The reason why .002 is selected is because an examination of the various metals disclosed the following figures:

HYSTERESIS CONSTANTS FOR VARIOUS GRADES OF IRON.

Names of metal.	Constant.
Swedish wrought iron well annealed......	.0010 to .0017
Annealed cast steel of good quality with little carbon	.0017 " .0029
Cast Siemens-Martin steel................	.0019 " .0028
Cast steel with plenty of carbon and wrought iron of poor grades...........	.0031 " .0054

The number of lines of force per square centimeter, raised to the 1.6 power, may try the ability and patience of readers, so Fleming's figures are given for iron magnetized from 1,000 to 10,000 lines of force per cubic centimeter. In addition, the total value of the product of the constant and the lines per square centimeter given raised to the 1.6 power are presented. The results are given in ergs per cubic centimeter, but the ergs are easily transformed into foot pounds or watts if required. The last line of figures in the table, giving the ergs absorbed by a cubic centimeter of iron carrying 10,000 lines of force, according to the formula, would be equal to about 10 foot pounds per complete cycle of magnetization.

As there are 10^7 ergs to a watt, it is evident the above table can be converted to English measure and watts if necessary. To illustrate the application of this table, consider the frequency of a commercial circuit carrying an alternating current as equal to

TABLE OF HYSTERESIS CALCULATED BY THE FORMULA.

Lines of force per sq. cm.	Value of $B^{1.6}$.	Value of $.002 \times B^{1.6}$.
1,000	63,100	126
2,000	191,300	383
3,000	365,900	732
4,000	580,000	1,160
5,000	828,800	1,658
6,000	1,111,000	2,222
7,000	1,420,000	2,840
8,000	1,758,000	3,516
9,000	2,122,000	4,244
10,000	2,511,000	5,022

120 cycles per second. If the degree of magnetization is equal to 10,000 lines of force per square centimeter, it will be equal to 6¼ × 10,000 or 62,500 lines of force per square inch. According to the table, $.002 \times 10{,}000^{1.6} = 5{,}022$ ergs per cubic centimeter per cycle. This would mean $120 \times 5{,}022 = 602{,}640$ ergs; but as 10^7 ergs equal one watt, 602,640 ergs $\div 10^7$ or 10,000,000 will be equal to .06 of a watt per cubic centimeter. A cubic inch of iron is equal to 15.625 cubic centimeters, which would mean $15.625 \times .06$ watt per cubic inch, a value equal to .9375 watt. Averaging 1 watt per cubic inch would mean at this magnetization 1,728 watts per cubic foot of iron.

Choice of Iron.—The choice of iron for the various purposes to which it is best suited is found by an examination of the area of the hysteresis curve representing a complete magnetic cycle. As shown, the area (Fig. 46) must be large if a permanent magnet is to be constructed. On the other hand, the area is smaller where such iron is used for dynamo work. If transformer iron is to be selected, the area is smaller still; in fact, it must be small or the hysteresis loss will be so great as to destroy the efficiency of operation of the transformer. The entire question of transformer design is related to the final question of lighting and power efficiency. To transmit electrical energy over a distance of many miles with economy it is necessary to limit the initial expense. This expense is divided up between the cost of the generating and receiving stations at each end and the investment required for the construction of the

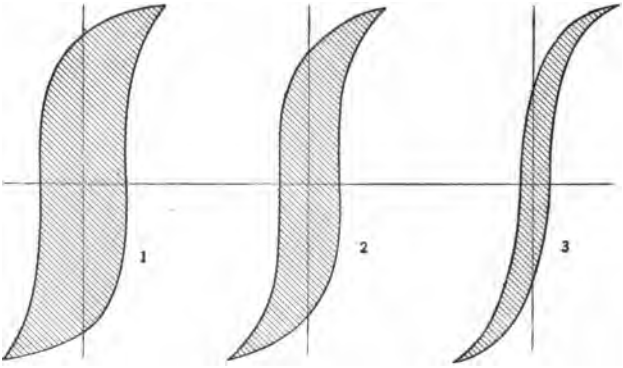


FIG. 46.—1. Area of curve large; metal suited to make permanent magnets. 2. Area of curve smaller; metal suited for dynamo magnets. 3. Area of curve very small; iron good for transformer construction.

line. But the most important feature of this system is that of the transformation of the pressure up and down at each end of the power line.

Curve of Hysteresis Loss.—Steinmetz constructed what is called the hysteresis curve (Fig. 47) in contradistinction to the hysteresis loops. The curve shows the relationship between the loss in ergs in the iron and the number of lines of force for a single cycle. The drift of the curve shows clearly the manner in which the losses in the iron grow with the increase in the magnetization. As long as the magnetization lies between zero and 5,000 lines of force the loss in ergs is slow in increasing. After passing this point, however, the rise is more rapid, and after the loss in ergs per cubic centimeter exceeds 2,000, the further loss increases rapidly. Dividing ergs by 10,000,000 or 10^7 will give watts; it is, therefore, a

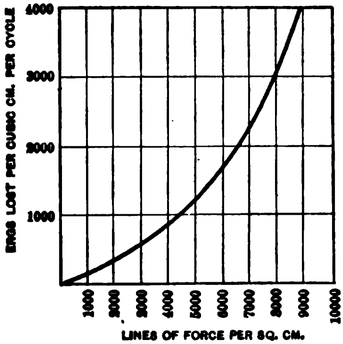


FIG. 47.—Steinmetz Curve of Hysteresis.

simple process in the calculation of hysteresis to judge of the relative value of different grades of iron by this means of comparison.

Principles of Design.—Not only in transformers, but in the armatures of direct-current dynamos and in the moving iron parts of many alternators, hysteresis occurs. The checking of it is one of the purposes of scientific investigation, as well as the limitation of other sources of loss. With regard to transformers, the following conditions must be observed:

First—The iron-core loss must not represent more than 3 to 4 or, if possible, 1 to 2 per cent. of the total load in watts. One per cent. is not too high for large transformers of many kilowatts.

Second—The drop in volts in the secondary must not be more than 1 or 2 per cent. of the total secondary pressure.

Third—The core must be kept cool by allowing at least 3 to 4 square inches of radiating surface per watt wasted in the iron.

Fourth—The winding of both primary and secondary coils must be large enough to radiate the heat they generate through C^2R loss. An allowance of from 2 to 3 square inches per watt wasted must be provided in the coil surface.

Fifth—Insulation of the best quality is necessary to withstand high pressures.

Sixth—Additional ventilation and cooling must be supplied to keep down the temperature of large transformers. Air blasts and oil are the favorite methods in vogue at present.

CHAPTER VI

WEIGHT OF TRANSFORMER IRON AND LOSSES.—LAG OF MAGNETISM BEHIND THE MAGNETIZING FORCE.—INFLUENCE OF MAGNETISM UPON THE SECONDARY COILS.—THE TWO CAUSES OF HYSTERESIS.—TRANSFORMER EFFICIENCIES.—CONSTRUCTION OF MODERN TRANSFORMERS FOR LIGHT AND POWER.—THE AGING OF TRANSFORMER IRON.—COOLING OF THE TRANSFORMER.—EDDY-CURRENT LOSSES.—VARYING THE THICKNESS OF THE IRON.—RATING OF TRANSFORMERS AS TO TEMPERATURE.—EFFECT OF HYSTERESIS AND EDDY CURRENTS DURING OVERLOAD.—EFFECTS OF INCREASED SIZE IN TRANSFORMERS.—SELF-COOLING TRANSFORMERS.—ADVANTAGES AND DISADVANTAGES OF OIL.

Weight of Transformer Iron and Losses.—All alternating-current apparatus makes use of sufficient iron to constitute an item of great loss when the entire weight is considered in connection with the loss of power such weight represents. Although an old table, the following figures, obtained from experimental data supplied by Professor Ewing and used by Gisbert Kapp, can be referred to for the purpose of finding out the number of watts wasted per ton of iron, and, in consequence, the horse-power dissipated per ton as well:

Lines of force per sq. cm. in the iron.	Watts wasted per ton of iron.	Horse-power wasted per ton of iron.	Lines of force per sq. inch.
2,000	650	.87	12,500
3,000	1,100	1.48	18,750
4,000	1,650	2.21	25,000
5,000	2,250	3.02	31,250
6,000	2,900	3.89	37,500
7,000	3,750	5.03	43,750
8,000	4,450	5.97	50,000
9,000	5,550	7.43	56,250
10,000	6,650	8.90	62,500

It is not an unusual thing for central stations to have from 20 to 100 or more transformers attached to their circuits, weighing on an average of from 100 to 500 pounds or over, according to their capacity. This being the case, if the figures given are taken to represent the weight of iron, it is evident that 100 transformers with 100 pounds of iron apiece would weigh 10,000 pounds or 5 tons. At an average induction of 7,000 lines of force per square centimeter, or over 40,000 per square inch, the loss of power per ton would be about 5 hp. For 5 tons of iron the total becomes $5 \times 5 = 25$ hp.; quite an expensive item if calculated annually at the rate of $50 per annum per horse-power, thus meaning a fixed loss of 25 × $50 = $1,250. In some central stations, supplying considerable electricity over scattered sections of a town or city, the number of customers may be so great that several thousand transformers are in use at once. At an average of only 50 pounds of iron apiece, 1,000 transformers would represent a total iron weight of 50 × 1,000 = 50,000 pounds, or 25 tons. At the same rate per square inch for the lines of force, the loss per ton of iron is 5 hp. This means a total annual loss of 5 × 25 = 125 hp., which, costing $50 per annum, would mean a net loss of $6,250 a year. The loss of power in the primary and secondary coils is not considered in this estimate, but it would mount up as well to important figures. Though a great saving in copper is made in the transmission and distribution of electricity by means of a high-pressure alternating current, a balance can only be properly struck if the iron losses and individual losses in the copper of each transformer are carefully considered.

Lag of the Magnetism Behind the Magnetizing Force.—The application of a magnetizing force to the iron is not sufficient to instantly magnetize it. A certain interval of time elapses before the lines of force appear in response to the magnetizing force. Hysteresis causes this lag of the magnetism behind the magnetizing force. The result, therefore, of a magnetizing force applied to a piece of iron would be a magnetization curve a little behind (Fig. 48) the ampere turns creating the magnetism. The magnetizing force naturally follows the sine wave, for the obvious reason that the current and pressure are developed as sine waves. The magnetizing force simply consists of the coil turns and the current; it therefore rises and falls as a typical sine wave as well. But the magnetism will not develop in this manner; its growth and diminution are formed in the hysteresis curves, with the difference, however, that when the change occurs slowly the curve is of a square, flat type, as shown in the illustration. It is also evident that the magnetism lags behind the electrical energy as found in the magnetic curve where it crosses the zero line to a degree dependent upon the responsiveness of the iron to slow or fast changes.

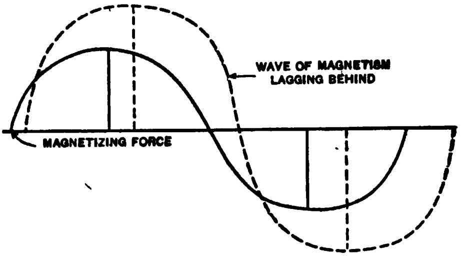


FIG. 48.—Relationship of the Magnetizing Force and Magnetism.

Influence of the Magnetism Upon the Secondary Coil.—The magnetism in the iron is the cause of the secondary developing its E.M.F. It is evident that the secondary E.M.F. is in perfect phase with the magnetism of the iron core. The degree of change represented by the rising and falling curve of magnetism is therefore an exact measure of the degree of change developed in the secondary coil in the way of electromotive force. The reason for this is found in the well-known fact that lines of force and turns which vary according to simple principles produce E.M.F. In this case the lines of force vary, but not as rapidly as the magnetizing force producing them vary. The coinciding of the rise and fall of the secondary E.M.F. (Fig. 49) with the rise and fall of the magnetism does not mean a current in the secondary which is in phase with its E.M.F. If the magnetizing force be plotted with its resulting E.M.F. in the secondary, and then the secondary E.M.F. be plotted with the current in the secondary, a greater difference of phase (Fig. 50) will naturally be found between the magnetizing force and the secondary current than can be explained by any other means than that of hysteresis.

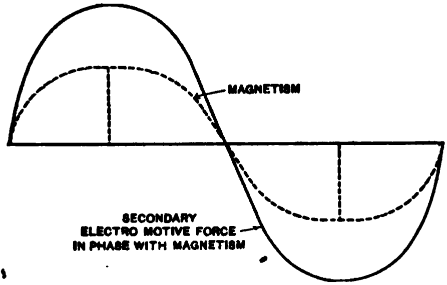


FIG. 49.—Relationship of the Magnetism and the Secondary E.M.F.

The Two Causes of Hysteresis.—From a physical standpoint hysteresis may be regarded as dependent in its manifestations upon two things: First, the degree of magnetization to which the iron is affected when the magnetizing force is applied to it; and second, the rate at which the magnetizing force is applied, withdrawn, and reversed. This has been described under the title of static and viscous hysteresis by comparing it with a weight drawn up and

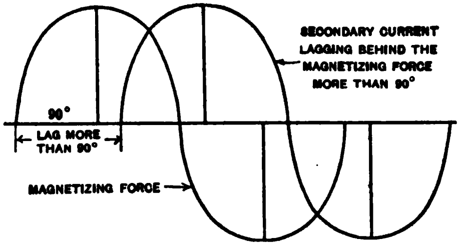

SECONDARY CURRENT LAGGING BEHIND THE MAGNETIZING FORCE MORE THAN 90°
90°
LAG MORE THAN 90°
MAGNETIZING FORCE

FIG. 50.—Relationship of the Magnetizing Force and the Secondary Current.

down through a thick, gelatinous fluid. To quote: "Apart from the fluid resistance, the work done in lifting the weight against gravity, say 100 times, is 100 times the work required to lift it once; but if fluid resistance comes into play, and if this varies as the square of the velocity of the moving body, then the total work done (Fig. 51) in lifting the weight through the fluid will be dependent also upon the rate at which the cycle is performed."

Transformer Efficiencies.—When the transformer is unloaded, that is, when the resistance of the secondary is that of an open circuit, the amount of energy wasted in the transformer is given by a formula, as follows:

Waste of power =

$$\frac{1}{2}\times B^2\times R_p\times\left(\frac{K}{4\times\pi\times T_p}\right)^2,$$

where B = the lines of force per square centimeter in the core, R_p the resistance of the primary coil, K the magnetic reluctance (equal to $l \div \mu \times q$, where l = the length in centimeters, μ = the permeability of the iron, and q = the cross-section in square centimeters), T_p = the turns of the primary coil, and π the value 3.1416. As this waste of energy is calculated from absolute units, the results would be ergs, 10,000,000 of which are equal to 1 watt. The answer, therefore, divided by 10^7 will give watts, or, if further divided by 746, will give horse-power. It is evident from an examination of the formula that as the magnetization of the iron of the transformer increases the loss increases as its square. The lesson

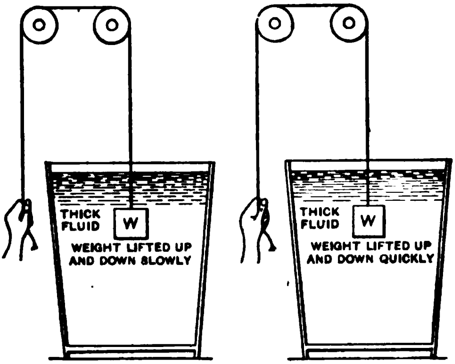

THICK FLUID
W
WEIGHT LIFTED UP AND DOWN SLOWLY
THICK FLUID
W
WEIGHT LIFTED UP AND DOWN QUICKLY

FIG. 51.

Simile to Hysteresis with a Low Rate of Reversal and Strong Field.

Simile to Hysteresis with a High Rate of Reversal and Strong Field.

to be learned from this is that the transformer must be designed to operate at a low magnetization when the lamps connected to the secondary are not in use. The other point of perhaps greater importance is that the energy wasted is proportional to the square of the magnetic reluctance K. The less the reluctance, therefore (Fig. 52), the less the value of the square of its value as indicated, and the less the watts wasted when the secondary is on open circuit. The expression is valuable in showing how a transformer with iron too well magnetized will be the means of dissipating a great deal of power. A feature in transformer construction is, therefore, the necessary bulkiness of them in order to obtain efficiency. A low rate of magnetization and the best quality of iron are to be considered as dominating principles.

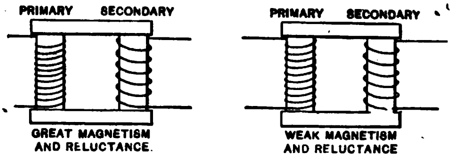

PRIMARY
SECONDARY
GREAT MAGNETISM AND RELUCTANCE.
PRIMARY
SECONDARY
WEAK MAGNETISM AND RELUCTANCE

FIG. 52.

Efficiency Low. Efficiency High.

Construction of Modern Transformers for Light and Power.—The transformers manufactured for practical use in the field of light, heat, and power are so constructed that their efficiencies vary with the load, as follows:

1. Efficiencies of a 150-kilowatt transformer of an E.M.F. of 500 to 15,000 volts and alternations of 7,200 per minute at different points of load:

Full load efficiency.............. = 97.5 per cent.
¾ load efficiency............... = 97.4 per cent.
½ load efficiency............... = 97.0 per cent.
¼ load efficiency............... = 94.9 per cent.

Other items of information: Regulation with a non-inductive load is to within 1.5 per cent. With a load having a .9 power factor the regulation is to within 3.5 per cent.

2. Efficiencies of a 375-kilowatt transformer of an E.M.F. of 500 to 15,000 volts and 7,200 alternations per minute at different points of load:

Full load efficiency.............. = 98 per cent.
¾ load efficiency............... = 98 per cent.
½ load efficiency............... = 96.6 per cent.
¼ load efficiency............... = 96.1 per cent.

Other items of information: Regulation with a non-inductive load, 1.4 per cent. Load having a .9 factor, 3.3 per cent. regulation.

The primary and secondary coils are divided into a series of smaller coils, but of great depth of winding apiece. The insulation of each coil is complete and distinct from its neighbor, whereby the following advantages are secured by such construction:

First, it divides the total E.M.F. between several coils, reducing proportionately the strain within an individual coil; second, it divides the E.M.F. in a single coil between many layers, thus reducing the potential between adjacent layers; third, it enables the coils to be spread apart at the ends, so that a very large surface is exposed to the oil used as an insulator and cooling medium; it also provides ample radiating facilities, besides thoroughly insulating the bent part of the coils; fourth, the transformer regulation is greatly improved; fifth, the winding may be readily connected in series or multiple, thus giving a wide range in E.M.F.; sixth, in case of damage to a coil another one may be substituted with little trouble and without it being necessary to return the transformer to its manufacturers.

The Aging of Transformer Iron.—A peculiar condition of affairs results from the aging of transformer iron. According to the records of one of the largest manufacturers in the country, as quoted, " It is not sufficient that the loss in a transformer be low when installed, for, as is now generally known, much of the iron that has been used in transformers when subjected to the conditions prevailing in continued service is subject to a material deterioration, more or less rapid, with the result of a corresponding material increase in the iron losses. In some cases this increase has amounted to a doubling of the loss found in the transformer when first installed." The importance of this statement cannot be overestimated, because it is evident that a careful examination of the iron (Fig. 53), from whatever source it may come, is absolutely necessary before it is used for transformer construction. It is therefore necessary to use all means that science can employ to select iron which, though no better than that of other lots so far as permeability, coerciveness, etc., is concerned, is still superior, in that it does not deteriorate because of an inherently stable character when in practical use.

Cooling of the Transformer.—Corrugated exteriors are made to provide a greater surface and thus cool the contents of the transformer more rapidly. The transformer proper is placed in a cast-iron box (Fig. 54) which is filled with oil. The outside of the box is ribbed to facilitate the radiation of heat, or otherwise enlarged by means of corrugations, etc. The oil acts as a conductor in transferring the heat to the outside of the containing cases. The additional feature is that of connecting the outside of the case to a water-circulating system to further facilitate its rapid cooling.

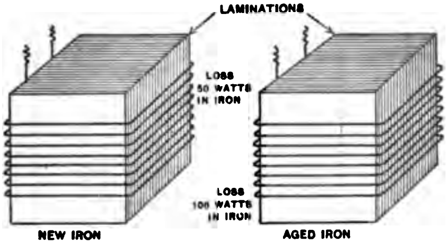


FIG. 53.—Comparative Loss in Iron through Hysteresis when Newly in Service and when Aged.

Eddy-current Losses.—In all cases where sheet-iron is alternately magnetized and demagnetized the effect of the lines of force is to create within the iron an E.M.F. which causes minute currents to flow in it. These currents are sufficiently minute to be of little consequence individually, but collectively they are of such importance that unless checked a considerable percentage of the available energy will be uselessly dissipated. The method employed, namely, that of subdividing the iron, is successful if means are taken to insulate the sheets from each other. The thinner the iron sheets the less the waste of energy through the generation of eddy currents (Fig. 55), and the thicker the sheets the greater the waste of power. Practice, however, shows that limitations of thickness are best found in a certain average, such as is commonly discovered in ordinary Swedish sheet-iron or its near equivalent of American manu-

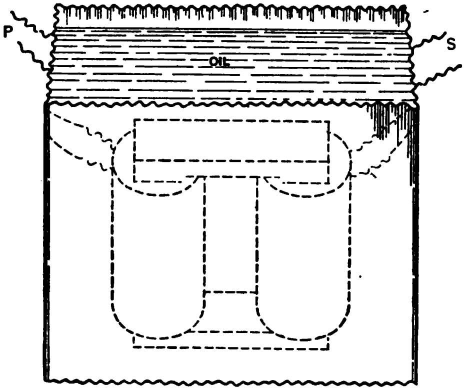


FIG. 54.—Transformer Placed in a Corrugated, Oil-filled Case for Insulation and Cooling.

facture. The formula for eddy-current losses takes into consideration the thickness of the iron, the volume of the iron, the cycles per second, and the degree of magnetization, as shown in the following symbolic arrangement of these quantities:

$$W = 1.645 \times V \times f^2 \times t^2 \times B^2 \times 10^{11},$$

where W = the watts wasted, 1.645 = a constant whose value is variable, though approximately as stated, V = the volume of iron in cubic centimeters, f^2 = the square of the cycles of magnetization per second to which the iron is exposed, t^2 = the thick-

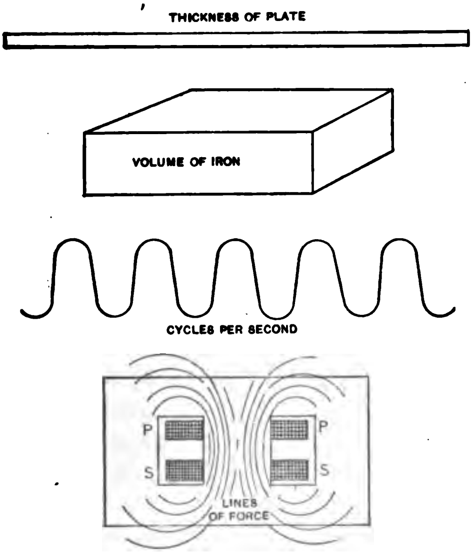


FIG. 55.—The Elements Limiting the Eddy-current Losses.

ness of the laminations in centimeters squared of the iron composing the transformer core, and B = the lines of force per square centimeter in the core. As may be noted by an examination of the formula, the watts wasted in the iron are directly proportional to the volume, indicating that the greater the weight of the core the greater will be the watts wasted through eddy currents. An increase in the frequency affects the iron somewhat differently, however; doubling this means four times the effect developed before, tripling it, nine times the original effect, etc., as noted by f^2.

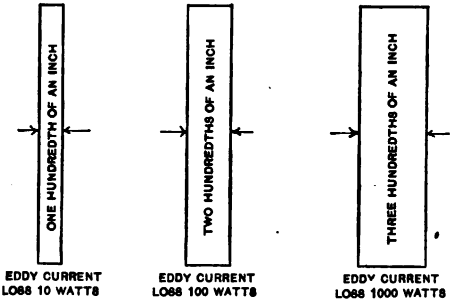

ONE HUNDREDTH OF AN INCH
TWO HUNDREDTHS OF AN INCH
THREE HUNDREDTHS OF AN INCH
EDDY CURRENT LOSS 10 WATTS
EDDY CURRENT LOSS 100 WATTS
EDDY CURRENT LOSS 1000 WATTS

FIG. 56.—Effect of Doubling and Tripling the Thickness of Core Plates of a Transformer.

Varying the Thickness of the Iron.—Increasing the thickness of the iron (Fig. 56) is evidently the means by which eddy currents are rapidly multiplied. The reason for this is the reduction of resistance and the increased E.M.F. developed in the iron through its greater effectiveness as an inductor. For instance, if an iron plate .1 of an inch thick generates E.M.F. in a given field of magnetism, and the thickness is increased to .2, then not only in this case is the E.M.F. doubled, but the resistance of the plate is halved (Fig. 57), thus raising the current to four times its original value. In other words, the most important practical elements in eddy-current losses are the thickness, the lines of force, and the frequency. The formula for E.M.F. which considers the relationship between the conductors, lines of force, and speed in an armature is applicable here in showing the nature of the increase in waste energy in the iron plates

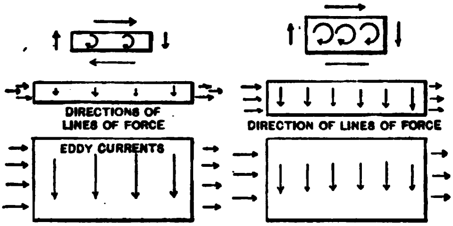


FIG. 57.—Effect of Thickness of Iron on Eddy Currents.

Eddy Currents Developed through Thickness of the Iron.

More Eddy Currents through Greater Thickness of the Iron.

through either an increase in the lines of force per square centimeter, the frequency per second of the current, or the greater or less thickness of the iron plates. To take a specific case, suppose it is desirable to know how many watts are being wasted in 1,000 cubic centimeters of iron, composed of plates of .1 of a centimeter thick, the iron exposed to a series of 100 cycles per second at a magnetization of 5,000 lines of force per square centimeter, then the following data appears: $t = .1$, therefore $t^2 = .01$; $f = 100$, therefore f^2 10,000; $B = 5{,}000$, therefore B^2 25,000,000; and $V = 1{,}000$ cubic centimeters. Applying these items to the formula give the following: Watts wasted in eddy currents: $W = 1.645 \times .01 \times 10{,}000 \times 25{,}000{,}000 \times 1{,}000 \times 10^{11} = 1.645 \times .01 \times 10^4$

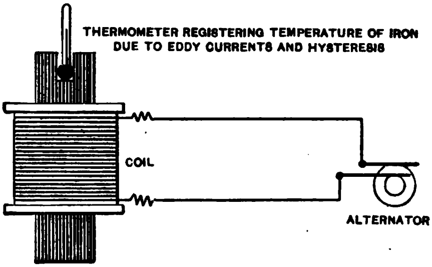

THERMOMETER REGISTERING TEMPERATURE OF IRON DUE TO EDDY CURRENTS AND HYSTERESIS
COIL
ALTERNATOR

FIG. 58.—Temperature of Iron Increased through Eddy Currents and Hysteresis.

$\times 25 \times 10^6 \times 10^3 \times 10^{11} = .41125 + 10^{18} \times 10^{11} = 41.125$ watts.

The feature that plays an important part in calculations of waste power in the iron is that of the rise in temperature. This increase in heat (Fig. 58) is due to two ineradicable causes: First, the heat of transformer coils, both primary and secondary; and, second, the hysteresis and eddy currents of the iron itself. The consequence of this heat is the increased resistance of the iron plates and the reduced waste of energy due to the eddy currents. On the other hand, the rise in temperature of the iron is a cause for a reduction in permeability, which, if permitted to reach too far, will not only affect the insulation and magnetizability, but absolutely limit the capacity of the transformer. Cooling methods are therefore advisable for purposes which affect the entire operation as well as any one particular part. The calculation shows that for commercial thicknesses of wrought iron or mild steel, as is commonly used in transformer construction, the eddy currents are comparatively a negligible quantity. Where only 40 or more watts are consumed from this cause by eddy currents at the magnetization given, namely, 5,000 lines of force per square centimeter, this induction means a hysteretic waste of $1{,}658 + 1{,}000 + 100 \times 10^7$, or 16.58 watts. But the value of 41 watts lost by eddy currents is based upon a thickness of .1 centimeter for the iron, as compared with the 16.58 watts lost through hysteresis. If the iron is reduced in thickness the eddy-current loss will diminish greatly. For instance, if the iron is taken as equal to .05 cm., instead of .1 cm., then the calculation gives a value of $1.645 \times .0025 \times 10^4 \times 25 \times 10^6 \times 10^3 \times 10^{11} = 10.28$ watts, or about one-quarter of the first value obtained.

As a centimeter is about .4 of an inch, .05 centimeter is equal to .02 of an inch, or $\frac{1}{50}$. The idea presented here is to show that the waste of power (Fig. 59) due to eddy currents will become very great unless the correct thickness of iron is adopted in the construction. In fact the figures show that doubling or tripling the thickness of the iron means four or nine times the waste of power; also that reducing the thickness to one-half or one-quarter means reducing the eddy-current loss to one-quarter or one-sixteenth of its former value.

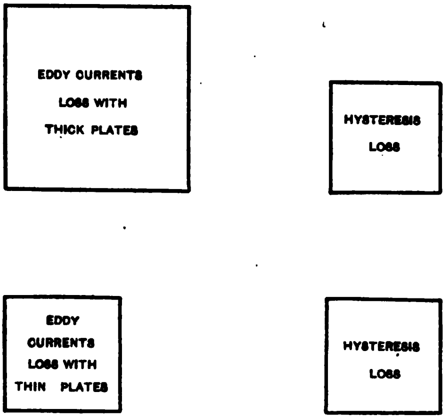


FIG. 59.—Relative Amounts of Power Wasted in Thick and Thin Plates by Eddy Currents and Hysteresis.

Rating of Transformers as to Temperature.—The American Institute of Electrical Engineers has passed certain rules and limitations regarding transformers, for the perpetuation of good service and a practical maximum working temperature in its parts, as follows: " In transformers for continuous service, a rise of temperature of copper not exceeding 50 degrees C. (90 + 32 = 122 degrees F.) as measured by change of electrical resistance of primary and secondary coils; and a rise of temperature of other parts not exceeding 40 degrees C. (72 + 32 = 104 degrees F.) as measured by a thermometer laid against the part, the core, for example, under normal conditions as to ventilation. In the case of transformers intended for intermittent service, or not operating continuously at full load, but continuously in circuit, as in the ordinary case of lighting transformers, the temperature elevations above the surrounding air temperature shall not exceed 50 degrees C. (122 degrees F.) as measured by resistance in electric circuits, and 40 degrees C. (104 degrees F.) as measured by the thermometer in other parts after the period corresponding to the term of full load. In this instance the test load should not be applied until the transformer has been in circuit for a sufficient time to attain the temperature elevation due to core loss. With transformers for commercial lighting, the duration of the full-load test may be taken as three hours, unless otherwise specified." A further suggestion made by this eminent body is that transformers should be overloaded 25 per cent. for a period of two hours, during which time the increase in temperature must not exceed 27 degrees F. over the ordinary full-load test, when they are to be rated for an overload of this value. If the lighting or power circuits cause a greater overload than this, the temperature requirements must be strictly complied with or the transformer will overheat, burn out, and thus become inoperative.

Effect of Hysteresis and Eddy Currents During Overload.—The effects of an overload on a transformer are discovered in the additional heating of the coils composing the primary and the secondary and possibly in the iron. The heating of the iron increases only because the hysteresis increases with any augmentation of the lines of force, or as indicated by the formula: Watts wasted $= nB^{1.6}$. The eddy-current loss will also increase if the lines of force increase, because this is proportional to $f^2 B^2$ in the formula, these being the variable factors. An overload does not increase the frequency f, but if it increases the lines of force per square centimeter B, then $f^2 B^2$ is greater than before only because B^2 is greater. If the magnetizing forces of the primary and secondary coils equalize throughout the process of underload, normal load, and overload, the iron core will not carry any more magnetism than a certain amount throughout these changes. As a result of such conditions, neither the hysteresis or eddy-current loss will increase; but an increase of lines of force would readily increase both.

Effects of Increased Size in Transformers.—A relationship that must be understood in comparing the losses of transformers of different sizes is one which affects their manufacture to a remarkable degree. It is that which explains the increase in heat with an increase in size, as follows: A given transformer taken as a standard, which has a certain loss in watts through causes already enumerated and a certain radiating surface (Fig. 60), will, in comparison with a transformer twice the size, show that the larger one has eight times the volume of metal, but only four times the radiating surface. In other words, the internal losses are eight times as great, while the power to radiate the heat is not more than four times that of the smaller size. The consequences of this state of affairs would obviously be a heavy rise in temperature, unless provision is made in one of two ways: First, to make the transformer very much larger, in fact so large that the radiating surface per watt wasted remains constant; second, to supply some means of dissipating the heat rapidly enough from the transformer to keep it at a safely low temperature. Various methods are employed in central stations and large power plants, among which may be noted the following: 1st, transformers designed in such a manner that their natural radiating surface is greatly increased by means of extensions and ribs, an expensive method of procedure; 2d, transformers cooled by placing the transformer in an oil bath,

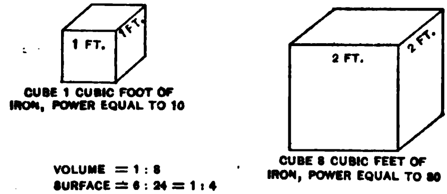

1 FT.
1 FT.
CUBE 1 CUBIC FOOT OF IRON, POWER EQUAL TO 10
2 FT.
2 FT.
CUBE 8 CUBIC FEET OF IRON, POWER EQUAL TO 80
VOLUME = 1 : 8
SURFACE ≐ 6 : 24 = 1 : 4

FIG. 60.—Case Illustrating the Transformer Iron when Increased for Extra Capacity, but Showing a Slower Increase in Radiating Surface.

the oil being in communication with an outer shell to which its heat is communicated rapidly; 3d, transformers supplied with an air-blast connected to blowers, which use up energy in keeping the transformers down to the right temperature; 4th, transformers cooled by means of a water-supply system, which, being pumped around (Fig. 61), means a loss of power in this direction; 5th, combination systems consisting of means representing more than one of the above items in the cooling process.

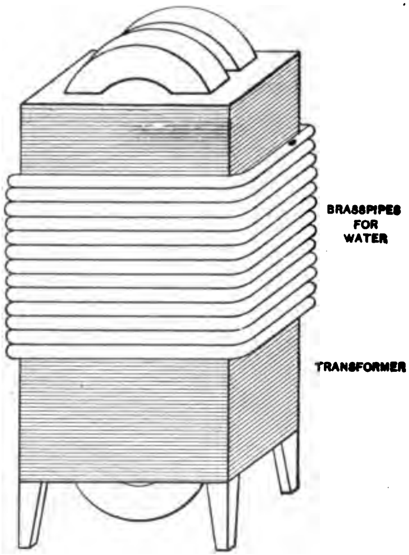


Fig. 61.—Transformer with Brass-pipe System for Circulating Water when Entire Device Rests in an Oil Bath.

Self-cooling Transformers.—By constructing a transformer of such a size that all its radiating surfaces are increased sufficiently to express the ratio of 2 or 3 square inches per watt would mean that a transformer whose core loss is 100 watts, and whose coil loss is 1,000 watts, would need at least 2,000 square inches radiating surface for its coils and at least 200 square inches for its iron surface. A self-cooling transformer is therefore best understood as one whose iron mass is about twice as great as it actually need be in order to keep the iron cool, and whose windings are relatively to this iron mass too small. The expense pertaining to a transformer built on these lines is too great to be justifiable. It is equivalent to a case where it is necessary to make a motor or dynamo twice as large as is actually required for the power in order to get sufficient cooling surface.

Advantages and Disadvantages of Oil.—The advantages of oil in transformer service are sufficiently great to make this application an idea of the highest value. In the first place, oil is an insulating fluid which preserves the integrity of the transformer without electrical risk. But it also adds an element of fire risk, which is its one great objection unless absolute precautions are taken to eliminate it. A spark flashing across cannot cause the injury to insulation with oil in use that would otherwise occur, but the comparative rapidity with which oil absorbs heat presents great advantages in holding the temperature down. Its use means a slow rise of temperature, an intact insulation, but a fire risk that may be regarded as dangerous. The appearance of sparks or disruptive discharges beneath the surface of the oil mean very little in comparison with the same discharges above or near the surface. When the inflammable parts catch fire with air present, they instantly serve as a huge wick and destroy the apparatus. Care in installation is a reasonably safe guarantee in such instances.

CHAPTER VII

REGULATION OF TRANSFORMER FOR LIGHTING.—CONSTANT CURRENT AND CONSTANT POTENTIAL.—CONSTANT-CURRENT TRANSFORMERS. — CONSTANT CURRENT FROM A DIRECT-CURRENT GENERATOR.—COMPARISON OF CONSTANT-CURRENT, CONSTANT-POTENTIAL, DIRECT- AND ALTERNATING-CURRENT SYSTEMS.—HIGH-TENSION SWITCHES.—SPARKING DISTANCES.—REQUIREMENTS OF SWITCHES.—POINT OF BREAKING THE CIRCUIT.—SWITCHES FOR 1,100 AND 2,200 VOLTS.—TRANSFORMER FUSE BLOCKS.—SINGLE- AND DOUBLE-POLE FUSE BOXES.

Regulation of Transformer for Lighting.—When the circuits attached to the secondary require current to supply the lamps, it is evident that the only source from which it can indirectly be expected to come is the primary of the transformer. But the electrical energy transmitted to the primary, as has been already shown, is not passed directly into the secondary. Instead, it is the means by which the transformer iron is magnetized and demagnetized, and magnetized in the opposite direction. In other words, the magnetism (Fig. 62) produced in the iron is the connecting link between the primary and the secondary when the power is either increased or diminished in the secondary. When the secondary, however, requires more current, it is only because the additional circuits connected to it are closed that makes this condition a matter of immediate response to the primary. This coil then permits more electrical energy to pass through it, or, to be more explicit, it permits more amperage to enter. But the vital point in the entire process is one upon which the candle-power of the incandescent lamp connected to the circuit of the secondary depends, namely, the preservation of the E.M.F. of the secondary. There is therefore this interlinked system to be considered: First, the readiness of response of the primary to changes of resistance of the secondary, as indicated by multiple lamp circuits being switched in and out. Second, the uniformity of the pressure of the second-

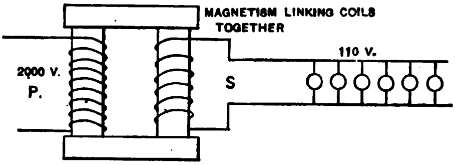


FIG. 62.—Entirely Transformed by Means of Magnetism.

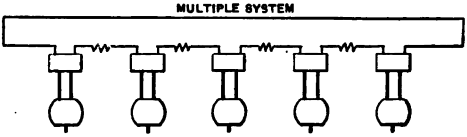


FIG. 63.—Constant-current System.

ary. The fact that a transformer is so constructed that the difference between no load and full load is the means of causing a perceptible rise and fall in electromotive force of the secondary is indicative of an absence of harmony in design. The heightened and lowered lamp candle-power would be an annoyance only relieved by a reconstruction of the primary, secondary, and iron cross-section.

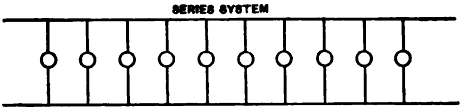


FIG. 64.—Constant-potential System.

Constant Current and Constant Potential.—The phrase constant current and constant potential was generally applied to the two great systems of direct-current lighting. The constant-potential system (Figs. 64 and 65) has been made the basis of electric

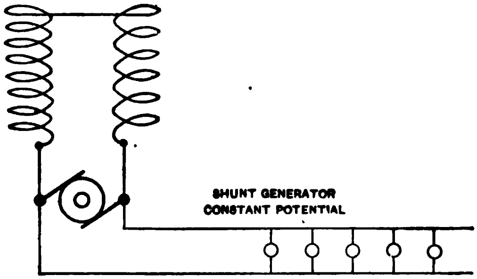


FIG. 65.—Direct-current Constant-potential System.

lighting by alternating currents as well as direct. In addition, a system has been devised by means of which a constant current (Fig. 63) is preserved in an alternating circuit as well. The broad classification of constant-current and constant-potential apparatus has been the distinguishing feature of the lighting done by such methods. As a general rule, the distinction is made more with reference to the lighting than the power. In this respect it may be added that the use of a constant potential is imperative in all cases where the ordinary incandescent lamp is employed. On the other hand, the arc lamp is the foundation of the division in the electric-lighting methods, though both constant-current and constant-potential lamps are in vogue. The same may be said to a limited extent of the incandescent lamp. There is a method of lighting by incandescents in which the voltage is not preserved, as in all such systems as are in ordinary use. On the contrary, attention is only paid to the preservation of a constant current, and this is the point of similarity between it and a constant-current arc-lamp system. In either case the value of the current is limited; the same class of apparatus supplying a constant current to the arc lamp can and has been used to supply a constant current to incandescents. The difference, however, is found in the pressure needed in the two instances for the different lamps. The constant-current incandescent does not require the same voltage as the constant-current arc lamp. For instance, in a 1,000-volt circuit of arcs and incandescents the number of arcs would be, with open-globe lamps, at least 20, whereas with incandescents the number of lamps would be from 50 to 100.

Constant-current Transformers.—In a transformer of this type the ordinary relationship between the electromotive forces of the primary and secondary are not preserved. Instead, certain features are introduced for the purpose of sustaining a relationship of which the outcome is a constant current. It is necessary in such a case, however, to preserve a constant electromotive force at the terminals of the primary coil. A system developed with this fundamental idea as a basis can be best understood as a series system of lighting. In the ordinary transformer the primary receives a given pressure; the current meets with a certain reactness, and, in consequence, only an amount of current passes into the primary able to do the work the secondary imposes upon it. But in all such cases both the primary and secondary coils are in a fixed position. Not only is this true, but the two pressures are fixed in ratio throughout the process. This, however, is the point of difference between the constant-potential and the constant-current transformer. In the constant-current transformer the primary is fixed in position, but the secondary is movable. In addition, the ratio of the two pressures is not preserved as in the former case. This presents the general idea: a transformer with a movable secondary and a ratio of values so crystallized that only the constant-current relationship is preserved. The theory underlying this construction is that a high inductance in the primary and secondary coils, but a relatively low mutual induction between them, will be the means of securing constant current in the secondary. Practical features of design dependent upon these ideas assumed the form of a transformer with a fixed primary, as stated, and a movable secondary coil. The core of the secondary, held in common by the primary as well, is long enough to permit the motion of the secondary when necessary. This motion is due to the repulsion which necessarily occurs between inductively related circuits. It is to be expected, as may be discovered by a citation of Lenz's law: That in all cases of electro-magnetic induction the induced currents have such a direction that their reaction tends to stop the motion which produced them. In other words, the coil of the secondary is free to move, and, in consequence, when the current in it is very strong, the reaction is great and the coil is repelled magnetically. When the current in the secondary is weak the repulsion is not so much in evidence, and, in consequence, the coils practically rest upon each other. Counterbalancing weights are used (Fig. 66), capable of adjustment, by means of which the secondary current is not only preserved at a constant value, but its value may be regulated to represent a certain amount. The degree of repulsion between the coils is not so great that they would of themselves be able to move against great friction. For this reason the two coils are so situated that while one is fixed the other is able to move freely up and down by the aid of a lever and weight system, as illustrated. The principle of regulation is readily understood by a consideration of the requirements outside. These are as follows: When a new lamp is added to a series circuit the resistance of the circuit increases. This means less current in the circuit and, in consequence, less current in the secondary coil. When there is less current in the secondary there is less repulsion between it and the primary coil. In consequence of this the secondary approaches nearer the primary; more current, therefore, flows through the secondary and more E.M.F. The effect of this is to repel the secondary to a position where it is able to give to the circuit enough pressure to keep all the lamps burning, and enough to fall within the requirements of its being constant. In transformers of the constant-current type of large size the primary is composed of two coils, situated above and below. In addition there are two secondaries free to move, as in the smaller size, but their movement is both downward and upward respectively. The primaries

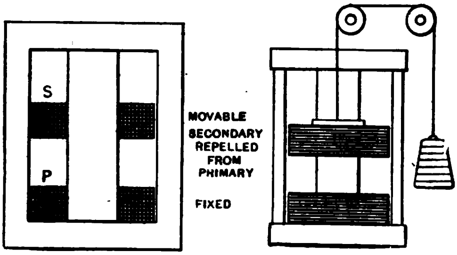


FIG. 66.—Constant-current Self-adjusting Transformer.

situated above and below are fixed in position, but the secondaries move, in the one case, upward to the upper primary and, in the other case, downward to the lower primary. In other words, the two secondaries move in opposite directions to each other when the transformer is in operation. This feature has been made use of to enable the two coils to so affect each other that the regulation for constant current is made without any counterbalancing weights. The series generator for arc lighting is also supplied with automatic means of an electro-mechanical nature for the preservation of a constant current. But the fact that in one case the current is made constant in a transformer, and in the other case in a generator, naturally calls for a distinct difference between them as pieces of operating mechanism.

Constant Current from a Direct-current Generator.—In a direct-current generator the armature revolves between the poles which produce the magnetic field, and is therefore the source of the E.M.F. In this respect the comparison might be instituted of the fields acting in the capacity of a primary, and the armature as a secondary. But this would be only for the purpose of showing that the armature is moved, because unless it is no E.M.F. can be produced. By this is meant that in the alternating-current apparatus, to which reference has been made, the current itself is moving, and therefore supplies the basis for inductive action. If the direct-current generator were so constructed that its field frame were laminated, then the passage of an alternating current through it would be the means of developing an alternating current in the armature. In this respect the generator becomes a transformer. But it does not belong to that category except in the sense that it is a transformer of a special type, in which mechanical energy is transformed into electrical energy. The electromotive force it generates with a constant speed and constant field is also constant, and it is therefore necessary to introduce means for obtaining a current whose constancy is preserved in spite of the fact that the E.M.F. under these conditions remains the same. The simple practice of shifting the brushes around on the commutator (Fig. 67) has been found the best method of accomplishing this purpose. The situation then presents itself of a generator in which every tendency of the armature to develop a stronger current is met by a movement of the brushes which cuts off the higher E.M.F. from the circuit at that instant. On the other hand, the tend-

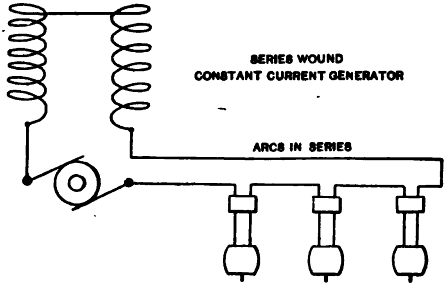


FIG. 67.—Series System, Constant-current, Direct-current System.

ency of the armature to produce less than the necessary quota of current is met by a movement of the brushes which increases the E.M.F. operating, and thus restores the current to its normal value. Both of these processes are necessary when the resistance of the outside circuit increases through the introduction of new lamps, or diminishes when lamps are removed from it.

Comparison of Constant-current, Constant-potential, Direct- and Alternating-current Systems.—The distinguishing features between the various systems employed for supplying arc and incandescent lamps with alternating and direct current can be best understood by a review of the methods involved, which may be stated as follows: 1st, constant potential for incandescent and arc lighting by means of shunt- and compound-wound generators; examples of such lighting found in central stations and private installations. 2d, constant current for arc lighting, generally of high potential and, in some scattered instances, of its use for incandescent lighting; the lamps in each case connected in the series. 3d, constant potential for incandescent lamps and arcs by alternating current; the lamp circuit exactly the same as with direct current, except that the current issues from transformers of various capacities. 4th, constant current for arc lamps and motors (Fig. 68) operated by alternating current. In all the cases cited it must be understood that the electrical energy, whether alternating or direct, is useful for motors as well. In this respect four classifications also appear, which in a general way cover all applications of electricity to this purpose. 1st, the use of constant potential for shunt-, series-, and differentially wound direct-current motors. 2d, the use of a constant current for series-wound direct-current motors. 3d, the use of a constant potential for induction, synchronous and non-synchronous alternating-current motors. 4th, the use of a constant current for special-constructed motors operated by alternating current. This *résumé* of the situation with respect to light and power is but a brief sketch of the enormous fields each represent in actual practice. The most prominent cases of constant-potential systems are found in the use of direct current for street-railway work and arc and incandescent lighting. Constant potential from alternating-current mains is applied in incandescent lighting, and to the running of induction motors of the single-, two-, and three-phase type. The recent introduction of the single-phase street-railway motor is merely an instance of a series-wound constant-potential motor finding a ready application to a service with a current theoretically well adapted to

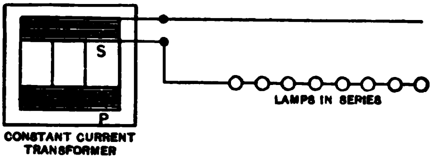


FIG. 68.—Constant-current Alternating System.

it, as street-railway practice can offer no salient objection to a change in the character of the current

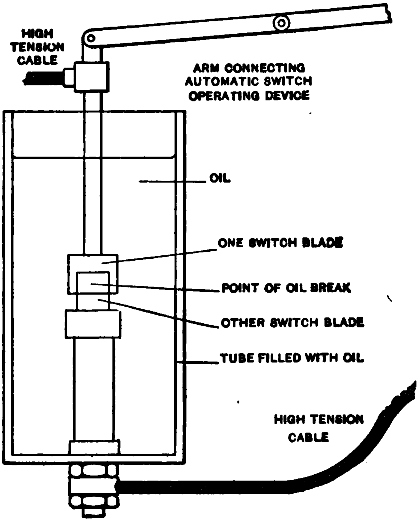


FIG. 69.—Principle of Breaking a High-tension Circuit in Oil.

as long as the requirements of such practice are fully complied with.

High-tension Switches.—To obviate the danger found in the sudden opening of a switch interrupting a high-tension circuit, an invention has been introduced by means of which such circuits are broken in oil (Fig. 69). Switches of this type are called high-tension oil switches. They are generally introduced in the main circuits leading from high-tension alternators. The fact that a circuit may be made and broken under oil has added greatly to the safety of installations requiring such protection. The commercial pressures now employed range from 2,000 to more than 60,000 volts, depending upon the nature of the plant. The safe handling of such pressures is best secured by automatic means, as it is evident that personal risks are exceedingly high, not so much because of the lack of insulation or other provision against danger as much as the possibility of the presence of a temporary fault, giving rise to possible fatality. One large manufacturing concern makes switches operated by means of a spring and a motor. It is called the machine-type oil switch and consists

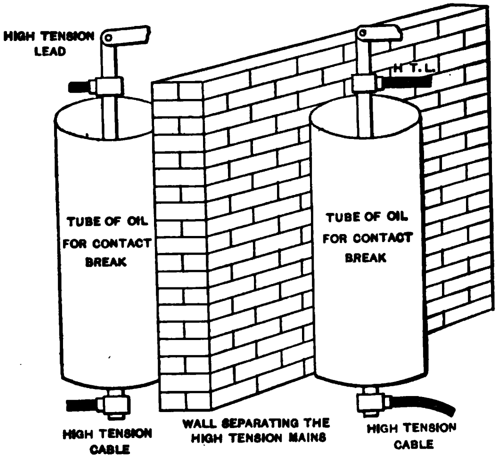

HIGH TENSION LEAD
H.T.L.
TUBE OF OIL FOR CONTACT BREAK
TUBE OF OIL FOR CONTACT BREAK
HIGH TENSION CABLE
WALL SEPARATING THE HIGH TENSION MAINS
HIGH TENSION CABLE

FIG. 70.—Principle of the Method of Securing a High-tension Break in Oil.

of a powerful spring, which acts as the operating force in opening and closing the switch. This spring, however, is coiled by means of a motor of small size. Every time the switch is opened or closed the motor operates automatically to an extent which is necessary to preserve the normal conditions. By this means the station attendant is free from risks inevitably present, due to the personal handling which would be otherwise obligatory. Long tubes are employed, to which each wire of the high-tension circuit is attached; and further protection against flashing is afforded by means of a concrete partition (Fig. 70) separating the high potentials of the said wires. Flashing is one of the accompaniments of high-tension circuits when made and broken under conditions which are not correct, such as defective insulation, bad contacts, or temporary defects in the switch, or in its design and construction.

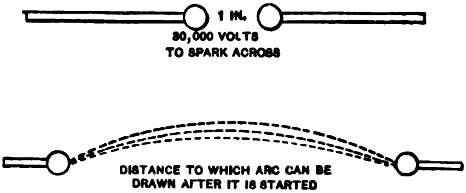


FIG. 71.—Small Distance to Start Spark, and Great Distance to which it can be Drawn with the Same Pressure of 30,000 Volts.

Sparking Distances.—It is important to note the sparking distances due to different pressures in connection with high-tension circuits. These distances naturally vary with external conditions, such as air pressure, moisture, etc. They are also increased in high-tension circuits by the development of peculiar conditions, which momentarily raise the pressure far above its normal value. According to the figures given, the potential necessary to jump 1 inch in air is 30,000 volts (Fig. 71), but it is also evident that if through any cause such as mentioned the spark does

Pressure in volts between terminals jumped by the spark.	Distance in inches.
4,765	.04
8,140	.08
11,307	.12
14,119	.16
16,664	.20
19,210	.24
21,823	.28
22,792	.32
24,153	.36
25,071	.40
26,255	.44
27,024	.48
27,765	.52
28,359	.56
28,949	.60
29,363	.64
29,837	.68
30,133	.72
30,547	.76
30,932	.80
31,198	.84
31,494	.88

jump across, then the arc forming will reach far more than a distance of 1 inch with a 30,000-volt pressure.

Requirements of Switches.—The requirements of switches for high- and low-pressure service may be enumerated for reference in the following list of items:

SWITCH REQUIREMENTS

1—Switches must break a pressure of from 2,000 to 60,000 volts.

2—Switches must be safe and sure in operation.

3—Switches must not burn contacts under any circumstances.

4—Switches must have perfect contact between parts that touch.

5—Switches must have a high efficiency, wasting little or no power.

6—Switches must have low heating, secured by ample cross-sections.

7—Switches must have interchangeable parts, thus securing a ready means of continuing the service in case of injury at this point.

8—Switches must be constructed of non-combustible material, and thus lower fire risks to a minimum in connection with them.

9—Switch parts must be capable of ready inspection for the ready discovery of faults in case they are developing under severe service.

10—No exposed metal parts, thus removing the likelihood of and freedom from accidental contact with conductors of any description.

11—Safety to attendants, through the systematic inspection of the switches and their design, and to cover the above features of construction.

Point of Breaking the Circuit.—The breaking of a circuit carrying an alternating current is accomplished in one of two ways: either to break the circuit when the E.M.F. has attained the very peak of its wave (Fig. 72), or when it has reached the lowest point of its wave. At the highest point or peak, the pressure being at its maximum, the arcing tendency is also at its greatest. According to the manufacturers of high-tension switches, to quote: "The tendency to arc is much greater with a lagging current where the peaks of the wave of E.M.F. and current are not coincident in time, if the circuit is broken when the highest point of the E.M.F. is reached. The point of breaking the circuit, if of high-tension alternating, is therefore that point at which conditions are most propitious—the point, in other words, at which a low pressure (Fig. 73) or zero is found in the alternating wave."

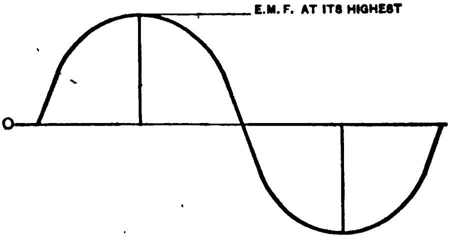


FIG. 72.—High-pressure Point of Breaking a Circuit.

Switches for 1,100 and 2,200 volts.—The so-called plunger type of switch was designed for the express purpose of eliminating arcing as far as possible. The principles upon which their construction is based may be covered by the following series of statements in this respect: First, the fact that arcs cannot be maintained after a circuit has been broken quickly and effectively; second, that the primary tendency of an arc is to expand until it has attained dimensions which the E.M.F. and resistance, according to Ohm's law, naturally demand; third, that an arc cannot be readily maintained in a confined space; fourth, that an arc will not resist a strong transverse current of air. These features are combined in this type of apparatus, and developed to meet the particular class of machines for which they were designed. The use of porcelain cylinders horizontally situated, and a marble slab upon one side of which the handle is mounted for the operator's use, and on the other side the mechanism which can be best described as given by the manufacturer's bulletin, as follows: "No

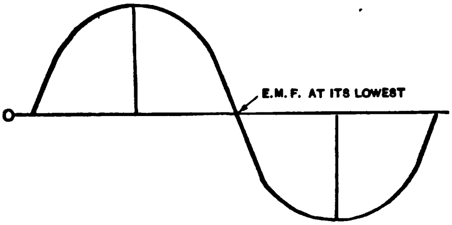


FIG. 73.—Lowest Point of E.M.F. to Break a Circuit.

charged metal parts are exposed on the operating side of the base. A cast-iron frame is mounted upon the back of the marble base, and serves as a support for the porcelain cylinders and as a guide for the operating-rod which passes through the frame and is controlled by a handle in front. The long handle furnishes a powerful leverage, and gives ease and certainty of operation. The handle being on one side of the marble slab and the switch terminals on the other side insures absolute safety to the attendant. One switch terminal is mounted at each end of a porcelain cylinder. Each cylinder has a half-inch bore, through which a copper rod or plunger

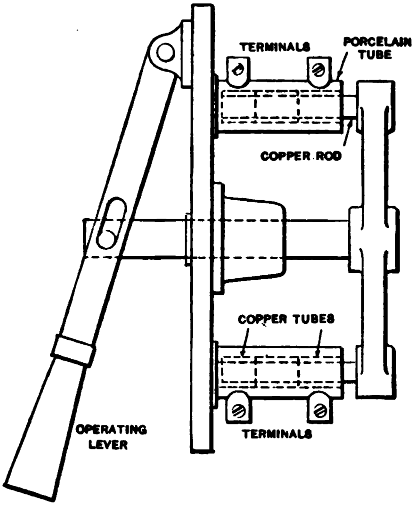


FIG. 74.—Mechanical Operation of Plunger Switches.

passes, making the electrical contact between terminals. The losses in consequence of these contacts are kept very low, contact being made on all sides of the cylindrical plunger (Fig. 74), which prevents heating and maintains a high efficiency of the switch. The plungers are self-aligning, and are entirely insulated from the iron cross-head. The only charged metal on the switch consists of the plungers and the two terminals on each porcelain cylinder. The cross-head, operating-rod, and handle are completely insulated from all live metal. In opening the switch the plunger is withdrawn from the lower contact, and the arc which tends to follow it is destroyed by the combined effect of the cooling action of the porcelain walls and the draft caused by the expansion of the heated air through the outlet from the porcelain tube.

"Those having one porcelain cylinder in each leg of the circuit, giving two breaks in series, are known as 'single break.' Switches having two porcelain cylinders in each leg, giving four breaks in series, are designated double-break switches. The breaking capacity of a switch being directly affected by the character of the load, or power factor, different ratings are necessary for non-inductive loads and for loads having more or less lagging current. Current furnished to incandescent lights supplied from transformers fairly loaded has little or no lag, and is therefore practically a non-inductive load. Current to operate motors, arc lights, or very lightly loaded transformers has a certain lag, the power factor being something less than 100. The power factor of

75 assumed in the table is a safe valuation for a circuit supplying general power service on many unloaded transformers. An increase in the frequency causes increased tendency to arc, and consequently decreases the current-breaking capacity of any given switch."

BREAKING CAPACITY OF PLUNGER SWITCHES.

Character of load.	Lighting or non-inductive load.				Power load with a power factor of not less than 75 per cent.			
Alternations	7,200		16,000		7,200		16,000	
Voltage..........	1,100	2,200	1,100	2,200	1,100		2,200	
Breaking capacity in amperes for single break....	100	50	100	50	60	25	25	
Breaking capacity in amperes for double break...	200	100	200	100	150	75	50	30

The principle followed out in switch design is one from which the best lesson can be taught as far as construction is concerned. It is the fact that the number of breaks in the circuit will to a certain extent determine the amperage that can be arrested. For instance, in the table given of such items, the breaking capacities of a single- and a double-break switch of the same number of cycles per second are as 2 is to 1. The rating of the switches differs, but their carrying capacities are all 200 amperes. The rating is therefore determined by the breaks in the circuit, and not, as might be supposed, by the actual capacity of the switch.

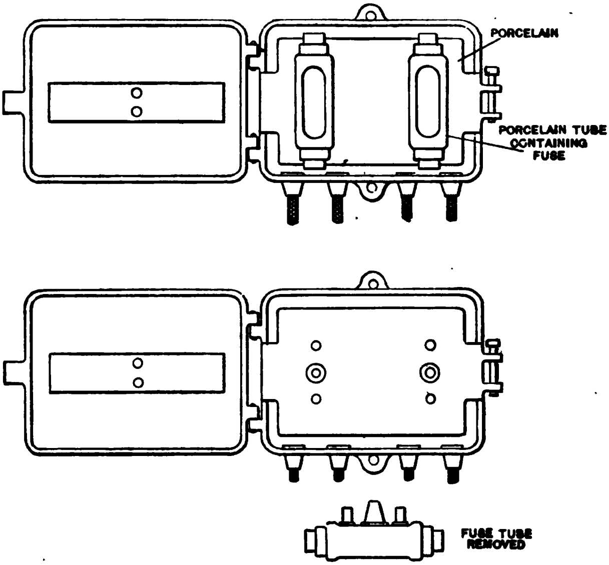


FIG. 75.—Fuse Blocks with Removable Tube Fuses.

Transformer Fuse Blocks.—The protection of the primary circuit against overflows of current is best secured by means of fuses attached to specially constructed fuse blocks. Fuse blocks are constructed (Fig. 75) so that they may be readily applied to service at any convenient point on or near the transformer. The fuse wire itself is made of an alloy of lead and antimony or other metal, which fuses at a fixed temperature with a given current. It is protected from injury by being inserted in a porcelain tube, which also serves to protect the lineman's hands from injury in case the fuse wire volatilizes while being inserted. It is recommended that lead wire be used for currents of 10 amperes or less, and for higher currents copper or aluminum. The sizes relating to these latter two metals, namely, copper and aluminum, are given as follows:

GAUGE SIZES AND CURRENTS OF COPPER AND ALUMINUM FUSE WIRES.

Current in amperes.	Size of wire in B. & S. gauge for copper.	Size of wire in B. & S. gauge for aluminum.
10 to 15	No. 24 B. & S.	No. 23 B. & S.
15 " 20	No. 23 "	No. 22 "
20 " 25	No. 22 "	No. 21 "
25 " 30	No. 21 "	No. 20 "

Single- and Double-pole Fuse Blocks.—For pressures of from 1,000 to 3,000 volts the regular single-pole fuse block is limited by its construction to the use of fuses of the character designated above. The double-pole fuse block employed for similar voltages is generally found in service with transformers not exceeding 10-kilowatt capacity of 1,000-volts pressure; and with transformers not exceeding 4-kilowatt capacity of about 3,000-volts pressure. The amperes vary in all cases, as far as these capacities are concerned, from 10 to 30. The unique features of construction are found in the use of porcelain tubes containing the fuses. These are air-tight, with the exception of a small opening at the back to allow gases to escape. Arcing is rendered impossible by the very nature of the space in which it occurs, the arc extinguishing itself automatically. The tubes are held in place by strong spring clips, which also serve as a switch, because when the tubes are lifted out only the primary of the transformer is entirely disconnected. Through the use of this principle the tubes can be lifted out and loaded with new fuses without unusual risk to the lineman. On the other hand, the blowing of the fuses means a sudden expansion within the tube, the effect of which is to destroy any arc about to form. Lateral expansion in this case is an absolutely reliable means of destroying arcs naturally tending to form with high-pressure circuits.

CHAPTER VIII

KINDS OF ALTERNATORS.—BELT-DRIVEN ALTERNATORS OF 16,000 CYCLES.—FRAME AND BEARING CONSTRUCTION.—ARMATURES OF ALTERNATORS.—ARMATURE COILS.—THE FIELDS OF ALTERNATORS.—FIELD-WINDING.—COMPENSATING WINDING.—DIRECT-CONNECTED OR ENGINE-TYPE ALTERNATORS.—FURTHER SUBDIVISIONS.—ROTATING-ARMATURE TYPE ALTERNATORS.—ARMATURE WINDINGS.—GENERATION OF PARASITICAL CURRENTS IN ARMATURE CONDUCTORS.—IRON-CLAD ARMATURES.—DIVISION OF THE FRAME.—FIELD WINDING.—ROTATING-FIELD ENGINE-TYPE ALTERNATORS.—THE ROTATING FIELD CONSTRUCTION.—ARMATURES OF ROTATING-FIELD ALTERNATORS.—TEMPERATURE OF ARMATURE.

Kinds of Alternators.—The various kinds of alternators can be classified, not only with respect to the character of the current they produce, but with regard to the particular method employed for driving them. With the purpose of distinguishing one from the other by means of the current generated, alternators are grouped as, first, single phase; second, two phase; third, three phase. By this distinction is meant that the single phase only consists of a simple cycle of E.M.F. and current, with the customary lag, the cycles ranging from 7,200 to 16,000 per minute, or from 120 to 266 + per second. The two phase does not necessarily mean any difference in frequency, but it does mean two different currents following each other by an interval of 90 degrees. Each of these currents consists, properly speaking, of an E.M.F. and current, the lag between them being such lag as would naturally arise in a circuit of the particular inductive features employed. The three-phase current means one with three independent currents co-operating to produce the sum total of power employed. Each of these currents consists, as in the preceding case, of an E.M.F. and current, with a lag dependent upon the conditions existing in the circuit traversed by it. The E.M.FS. are 120 degrees apart in this instance, thus giving three distinct currents to 360 degrees. In the two-phase, the difference being 90 degrees, there are four distinct currents to 360 degrees. Alternators producing these currents are, therefore, of three types, as stated, but

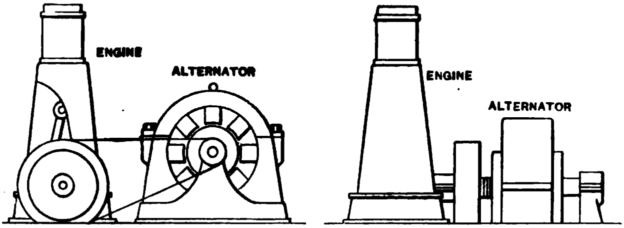


FIG. 76.

Belt-driven Alternator. Engine-driven Alternator.

they are generally classified from a constructive standpoint (Fig. 76) with regard to their being, first, belt-driven; second, direct connected or engine type.

Belt-driven Alternators of 16,000 Cycles.—Single-phase belt-driven alternators of a pressure of 1,100 and 2,200 volts represent one class of the standard types serving for purposes of light and power. They possess certain features of construction as regards their frames, armatures, fields, and method of regulation which require detailed description in order to present the salient facts embracing this particular department of light and power service.

Frame and Bearing Construction.—In this class of apparatus the lower half of the field casting and the entire base or support of the machine constitute one piece. By means of this manner of casting the entire machine in one, with the exception of the upper half of the field frame, great advantages are gained with

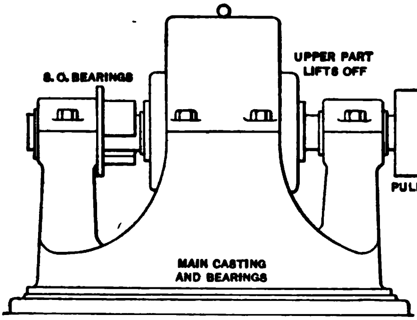


FIG. 77.—Analysis of Construction of Frame.

respect to the purely constructive features, as follows: The bearings are readily made self-aligning, thus adding greatly to the smoothness of operation of the alternator. They are made self-oiling, thus enabling all lubrication to be carried on automatically, and therefore without cost or attention. The fact that the upper half of the frame can be lifted off (Fig. 77) means ease of access to the armature and, if necessary, readiness of repair or substitution. The frame itself is not very massive, due to the fact that a moderate belt speed and a reasonable number of revolutions per minute are employed. Some figures covering a few sizes will show the relationship between speed, capacity, weight, etc., as well as the pulley dimensions required by manufacturers:

Kilowatts capacity.	No. of poles.	Rev. per minute.	Belt speed, ft. per min.	Weight.	Diam. of pulley, inches.
45	10	1,600	4,607	3,230	11
60	12	1,335	4,543	4,180	13
90	14	1,145	4,488	6,430	15
120	16	1,000	4,450	7,970	17

A complete description would include the fact that these dimensions refer to a two-bearing machine throughout of the specified frequency of 16,000 cycles per minute. For three-bearing machines the items are given as follows:

Kilowatts capacity.	No. of poles.	Rev. per minute.	Belt speed, ft. per min.	Weight.	Diam. of pulley, inches.
300	32	500	4,712	32,380	36
400	36	445	4,776	37,700	41

An interesting feature to note is the change in weight with an increase in capacity. In this respect a 60-kilowatt and a 120-kilowatt alternator of about the same belt speed, though their poles vary as 12 to 16, are about double the weight of each other: for instance, one weighing 4,180 pounds, the other 7,970 pounds. This may be also noted in the 45- and 90-kilowatt machines, whose belt speeds are respectively 4,607 and 4,488, and their weights 3,230 and 6,430 pounds. The poles differ in this last case as 10 to 14. This means, roughly speaking, that the increase in weight is proportional to the horse-power if the speed remains constant, though other influences affect this conclusion in practice.

Armatures of Alternators.—Armature cores are composed of many sheets of wrought iron or well-annealed steel (Fig. 78) bound together by means of bolts or clamps. The laminations, as they are called, are punched out of large sheets by means of a stamp and die. One of the most important of all features to secure is that of ventilation. This is, it might be said, the vital factor in determining whether or not a machine will exercise its full capacity without burning out under the strain. To secure this desirable feature ducts are made in the stampings, by means of which air is constantly circulating through the armature core. In fact, the greater and more successful the effort made to ventilate the armature the cooler it will run, and the better able it will be to stand full load throughout a long period of time, as well as more than the normal load for a short time without overheating.

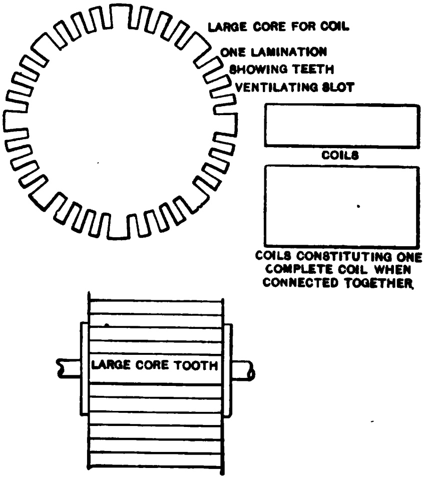


Fig. 78.—Details of Construction Showing Core of Armature Coils and Ventilating Slots.

Armature Coils.—In modern alternators of this type the armature coils are formed by machine. They are machine wound and formed and insulated before being ready for use. By this means the coils are simply placed in position without further bending. This means the preservation of the insulation when mounted on the armature for service. To make this point still clearer, it may be said that after a coil is formed and finished, if bent, it is apt to crack, and, therefore, freedom from this necessity is a distinct advantage in construction. Of the particular types given, the coils are slipped over the teeth; thus, a single coil is taken and placed on a tooth, thereby constituting an element of the winding equal to one armature pole. Larger machines of from 250 to 400 kilowatts are wound by means of heavy copper strips, instead of formed insulated coils. After the formed coils are placed in position they are still further secured by means of wedges of wood or fiber. These wedges fit into notches in the core, and act as effective means of holding the coils in solidly and without affecting their insulation. They are serviceable subsequently, by permitting the coils to be removed when repairs or substitutes are to be employed. By this method an entire armature may be stripped of its old winding and rehabilitated without delay. The idea of using formed coils not only represents a part of alternating-current practice, but is a distinct feature of direct-current practice as well. It is a highly ingenious method of rapidly replacing and repairing coils in whatever capacity they may be used. The entire series of coils is connected together in such a manner that one coil generating E.M.F. in one direction does not oppose the E.M.F. of a coil generating E.M.F. in an opposite direction. If, for instance, the current in one coil circulates in the direction of the hands of a clock, and the current in the neighboring coil in the opposite direction, namely, opposite to the direction of motion of the hands of a clock, then an ordinary connection of end to end will not do. The ends of coils must be connected so that the current flows continuously with each individual cycle, though reversing at the next that follows. If the coils are wound in opposite directions, then the inside of one is joined to the outer end of the next, etc.

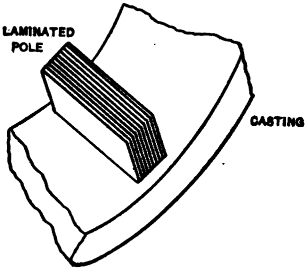


FIG. 79.—Casting with Pole Embedded.

The Fields of Alternators.—The details of construction with respect to the fields of these alternators betray interesting features. For instance, the field poles are not made of solid iron (Fig. 79), but of thin plates like the armature. These plates are held in position by being embedded in the yoke or frame composing the machine. They are thus a part of the frame to the extent at least of being inseparable from it. The iron is poured into the mould while the poles are in position, and thus becomes incorporated with them. Whenever varying currents are employed or generated it is almost compulsory to use laminated iron to avoid the effects of eddy currents. In this respect it may be mentioned again that the lamination reduces the eddy currents, though the degree of coercive force required is a measure of the hysteresis developed during one cycle. The fact that eddy currents are so greatly reduced —which phenomenon, it may be added, is a very marked one with solid poles—means a low temperature when the machine operates. A low temperature means a greater capacity and a stronger field. A stronger field than would be otherwise attainable is also possible with very permeable iron, such, for instance, as that composing the laminated poles. If the poles heat up, as they would if made of solid iron, unless a large air gap is used, then the field winding also heats, and the current it can carry is greatly reduced. This naturally means a weaker field, not directly due to the generation of eddy currents, but indirectly as shown. It is quite evident that unlaminated poles, in a machine of many poles, would mean considerable watt loss collectively. This eddy-current loss is the same for each pole, so that in a series of alternators of 10, 12, 14, 16, 32 or 36 poles, as given in the tables, the total loss, on the basis of 50 watts per pole, would be 500, 600, 700, 800, 1,600 or 1,800 watts for all the poles given. This eddy-current loss, it may be stated, is due to the rapidity with which the armature passes the poles of the separately excited field.

Field Winding.—The fields are not supplied with one but with two distinct windings. One of these windings consists of the regular separate source of excitation by means of which the normal field strength is obtained. The other is a winding whose influence is compensatory (Fig. 80), in that it is the means by which the fields are strengthened when the load increases and weakened when the load diminishes. The first winding is supplied with direct current from the exciter, which is only a small, separately driven, direct-current generator attached to the engine or dynamo. By means of this current the fields are so excited that the full pressure of the alternating current is obtained at no load. It is evident, however, that by loading up the alternator the

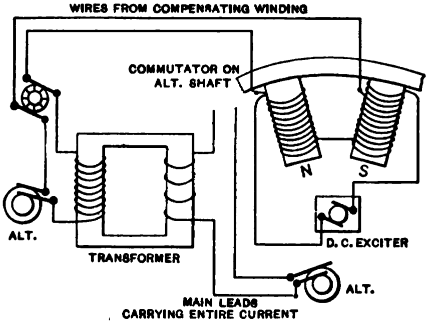

WIRES FROM COMPENSATING WINDING
COMMUTATOR ON ALT. SHAFT
N
S
ALT.
TRANSFORMER
D. C. EXCITER
ALT.
MAIN LEADS CARRYING ENTIRE CURRENT

FIG. 80.—Connections to Secure Compensating Winding.

drop of potential at the least will be sufficient in the armature coils to lower the available E.M.F. at full load.

Compensating Winding. — The compensating winding, or second set of turns on the field, receives its current from what may be called a separate current generated in the armature and rectified to pass into the compensating turns. A separate armature winding is connected to a transformer's secondary and its current rectified by means of a commutator. This enters the fields to a greater or less extent as follows: When the other transformer winding, consisting of a few turns carrying the main current, is very heavy, its effect upon the transformer is to permit a heavy current to pass out of the secondary, and, being rectified or commutated, a heavy current enters the compensating field turns. By means of this idea it is readily perceived that when a heavy current is demanded of the armature a heavy current must enter the compensating field turns, and thus keep the alternator pressure constant for all loads.

Direct-connected or Engine-type Alternators.— Where large installations are put in for single-phase lighting and power, the equipment is of the direct-connected or engine type, for reasons that have become apparent as follows: First, the advantage of large direct-connected units may be found in decreased floor space; second, an advantage may be found in decreased noise; third, a marked reduction in operating expenses is another distinct feature of this system; fourth, an increased efficiency results from the method of direct connected in comparison with belted connection between the engine and dynamo.

Further Subdivisions.—The general method of connecting up the generator and engine means a further classification into what may be called as follows: First, direct-coupled machines, which are provided, according to the manufacturer's description, with two bearings and a shaft, and are arranged to be connected, by a flexible coupling or otherwise, to the shaft of the engine or other source of power; second, engine-type machines, in which the rotating part of the alternator is mounted on the extended engine shaft (Fig. 81) and becomes a part of the fly-wheel capacity of the engine. In this type, as manufactured, the bearings and shaft are a part of the engine and are not furnished with the alternator. Engine-type alternators may be still further subdivided into two classes, which are entitled: Rotating armature types of machines and rotating field types of machines.

Rotating-armature Type Alternators.—In this particular class of single-phase alternators a cast-iron spider is employed, upon which is built up an armature consisting of a laminated steel rim. This armature surface is grooved in a direction which permits the coils to be laid longitudinally. In addition to the grooves are other openings, added during the design, to secure a better ventilation when in operation. Thus, the armature is only a broad, wide rim when completed, very much like a fly-wheel, except for the fact that conductors are attached to it to generate the necessary current. By supplying grooves at right angles to those parallel to the shaft these armatures are kept cool when in operation to a much greater extent than if the conductors were merely buried in the slots without this provi-

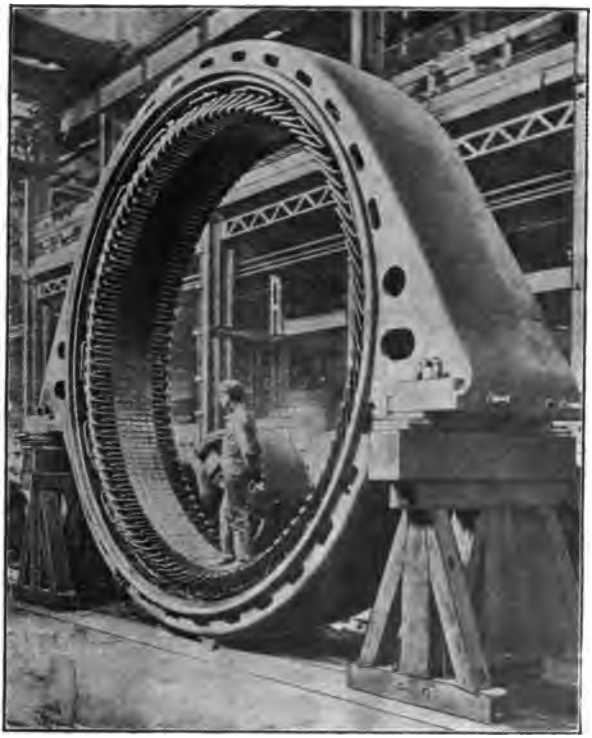


FIG. 81.—Stationary Armature for 750-kilowatt Alternator.

sion for lowering their temperature through radiation. The core as well as the conductors is kept cool by this means. The core heats through the hysteresis of its iron, but the conductors may heat through another reason than that of the current and resistance, as will be presently described.

Armature Windings.—As a general rule the windings of large armatures may be classified as follows: First, armatures wound with wire of regular insulation and standard size; second, armatures wound with straps forged into the necessary shape; third, armatures wound with bars, bolted and secured in a firm and reliable manner. As regards the first method, namely, wire winding, the conductors are treated as they would be in any similar case, that is: well insulated and bound into position; they are chosen of a size to carry the requisite power without overheating. Armatures wound with straps, however, are employed for machines of low voltage and great current capacity, the straps being carefully insulated. A feature of the wire and strap winding is that neither is subjected to mechanical bending when placed permanently in the slots. All such bending in the case of the wire is done when the wire is formed originally into coils. In the case of straps, it is not necessary, as they are of such a shape as to be ready for fitting into the slots, being secured there by wedges of hard fiber. The bar windings are held in place by the teeth, after care has been taken to insulate them. They are slipped into the slots from one end of the armature, entering them and being held by their trapezoidal shape. The end connections are obtained by means of other connecting bars and bolts. In this case no band wires are necessary on the armature, as the teeth hold the bars firmly in position. The tooth in a sense overlaps the bar on each side; this not only holds it in place and prevents it from falling out, but it acts to prevent an undue generation of parasitical currents in the broad copper bars.

Generation of Parasitical Currents in Armature Conductors.—What are called parasitical currents in armature conductors do not differ essentially from what are called eddy or Foucault currents. In other words, the generation of E.M.F. in a mass of metal moving within a magnetic field means the circulation of a current in an eddy if the metal mass is not subdivided at right angles to the direction of flow. For instance, as is well known, the body of iron constituting an armature core would develop enormous currents if the iron mass were not subdivided at right angles to the longitudinal direction of flow of the current. In the same sense a solid and broad copper conductor sweeping around through the lines of force, though it creates a current longitudinally under ordinary conditions, will not fail to develop eddies of electricity, due to the fact that part of the conductor is under the edge of the pole piece while the rest is comparatively free from lines of force. This means that a broad band of copper is developing E.M.F. in one-half its body longitudinally, the other half being neutral and unaffected. It therefore provides a return circuit for the E.M.F., and as a logical consequence a powerful current, called for purposes of distinction a parasitical current, will flow, generating great heat and wasting the energy otherwise available. The partial overlapping of the teeth over the copper bar reduces the surface exposed to the differences of all and no field spoken of, to a minimum. The result of this is a reduction of waste energy to its lowest terms, and a corresponding increase of efficiency to a high point commensurate with such precautionary measures. The name given to this class of armatures through such peculiarities of construction is "iron-clad."

Iron-clad Armatures.—This type of armature is considered superior, through its construction, to the ordinary types so much in vogue. Protection to the conductors is one of its main features, a form of protection that proves of the utmost value during the period of installation. To entirely remove the possibility of injury to conductors, they are not placed in position on the armature in some instances until it has been mounted, put in place, and keyed to the engine shaft. Then the conductors are slipped into their various grooves, secured permanently by bolting or otherwise, and connected ready for use. It must be understood that in this case it would be necessary to have removed the movable half of the frame in order to conveniently accomplish the work involved in the rehabilitation of the armature with its conductors. This is done by making the frame divisible in one of two ways.

Division of the Frame.—If the line of division in the frame is vertical it may be parted so that one-half is removed during the winding. Very large machines are separable in this manner, machines whose capacities vary from 500 to 1,500 kilowatts and over. When the line of partition is horizontal the lower casting is massive, with great shoulders which rest upon the guide plates. Upon this casting the upper half of the field rests, and into both the lower and upper castings the laminated poles are held. The laminations are fine enough to remove the risk of much wasted power through eddy currents. The quality of the mild steel, highly annealed, of which they are composed, is sufficiently good in modern practice to be a guarantee of high magnetic efficiency in this respect.

Field Winding.—Winding the fields upon forms is not a new idea, but the coils thus made consist of copper strap bent upon edge and afterward insulated. The coils are supplied with lugs or brackets to receive the bolts which secure them to the field frame. The lugs bear only a small surface of the coil, and this surface is easily insulated. The coils of smaller machines are composed of wire, instead of copper strap. Simplicity of construction and high efficiency are the features aimed at and secured by the methods of modern design. Large alternators are now regarded as involving no more questionable factors than large engines. In fact, the art has developed, so far as design and construction are concerned, to such a point that the method is practically non-experimental, and the best results are always expected, both in finish and efficiency.

Rotating-field Engine-type Alternators.—The alternator producing single phase is provided, as stated, with either a revolving armature or a revolving field. Where a revolving-field type is employed a series of advantages are gained, which may be enumerated as follows: First, the armature, being stationary, may be insulated in such a manner that no question can arise as to its failure through service, except due to extraordinary circumstances; second, a very much higher voltage may be developed by this type, due to the superior insulating methods which may be employed; third, a very much greater current can be generated; fourth, only the field current passes through the collector rings, instead of the current of the entire generator.

The Rotating Field Construction.—The laminated plates, of which this type of armature body is made, overlap and are held together by bolts. The construction of the field is such (Fig. 82), to quote the manufacturer, as to make a steel-rimmed fly-wheel which is self-supporting. The bolts and the friction between the plates make the steel rim of a construction similar to that which is frequently employed in fly-wheels. The rim is of sufficient strength in itself (Figs. 83 and 84) to resist centrifugal force without bringing undue stress upon the central cast-iron spider, the function of which is really to hold the outer rim in proper position. No poles can loosen, owing to the construction, and the ventilating disks in the armature provide means by which a constant circulation of air is made possible. A rotating field therefore means, in an engineering sense, great

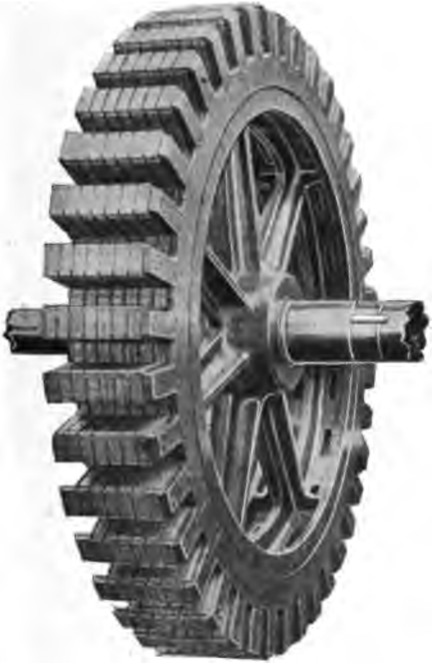


Fig. 82.—A Revolving Field Ready to Receive the Coils.

advantages over a stationary field machine. The positive construction of the rotating field, its extraordinary ventilation, its high flux, and its relative lightness in weight represent features of interest and importance.

Armatures of Rotating-field Alternators.—The armature consists of a laminated ring with slots on its inner surface. It is supported, as a rule, in very large machines by a massive casting or yoke provided with every means of ventilation. The use

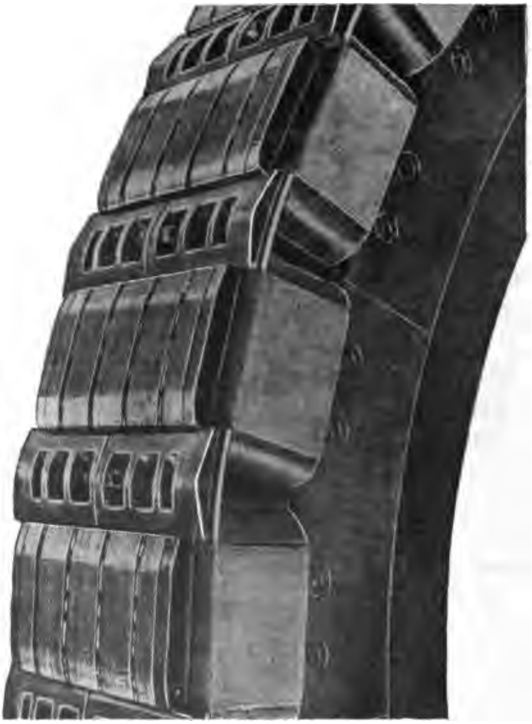


FIG. 83.—Portion of a Rotating Field Showing Coils in Place.

of bars set into the slots (Fig. 85) with bolted connecting pieces ending in cables at the point of exit of the current covers the main features of the constructive details involved. The armature winding is tapped at points which have the proper phase relation, and the conductors from these points are carried through the frame to the terminals, in fact

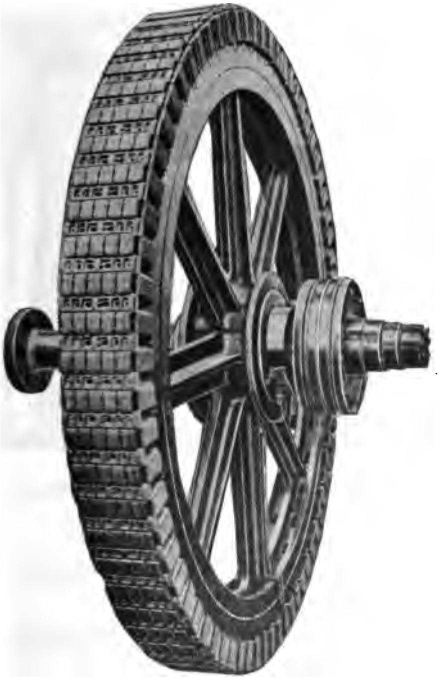


Fig. 84.—Rotating Field for a 300-kilowatt Single-phase Alternator Complete with Coils.

practically composing them. Standard frequencies are 3,000, 3,600, and 7,200 alternations per minute. Regulation of from 6 to 8 per cent. can be obtained with non-inductive loads; this will vary according to the character of the load in other respects, though it may be taken as a fair average.

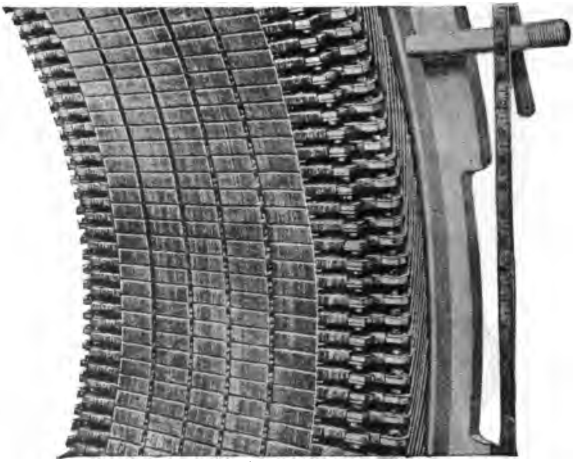


FIG. 85.—Portion of a Stationary Armature for Rotating-field Alternator. Concave View.

Temperature of Armature.—The determining and limiting influence in all armatures is the temperature to which they rise when developing or taking current. Alternators of this type are supposed, if well designed, to carry full load for 24 hours with a rise in temperature in any part not exceeding 104 degrees F. above the surrounding air. This is with a power factor of 90 to 100 per cent. With a 25 per cent. overload and the same power factor, they are supposed to be limited in their rise of temperature for a 24-hour run to not exceed 120 degrees F. above the surrounding air. With a 50 per cent. overload and the same conditions the temperature rise is not supposed to exceed 140 degrees F.

CHAPTER IX

ALTERNATORS IN SYNCHRONISM. — MECHANISM FOR OBTAINING SYNCHRONISM.—SYNCHRONOUS CROSS-CONNECTIONS.—SYNCHRONISM WITH HIGH-TENSION ALTERNATORS.—SYNCHRONISM FOR TWO- AND THREE-PHASE ALTERNATORS. — HIGH-TENSION POLYPHASE ALTERNATORS IN SYNCHRONISM. — ALTERNATING-CURRENT POTENTIAL REGULATORS.— SINGLE-PHASE MOTORS.—SELF-STARTING SINGLE-PHASE MOTORS.—MAKING TWO PHASES FROM ONE PHASE. — SINGLE-PHASE, SERIES-WOUND, SELF-STARTING MOTOR.—DEFECTS OF THE SINGLE-PHASE, SERIES-WOUND MOTOR.—PRACTICAL CONNECTIONS OF A SERIES AND SYNCHRONOUS MOTOR.—ADVANTAGES OF THE SYNCHRONOUS MOTOR. — ROTARY CONVERTERS AND SYNCHRONOUS MOTORS.

Alternators in Synchronism.—When two or more alternators are connected in parallel, certain conditions must be fulfilled before they can be permitted to send their respective currents into the main supply circuit. These conditions can be tersely expressed in the following terms: First, the machines must generate the same electromotive force; second, the machines must produce exactly the same frequency; third, the generators must be in perfect phase with one another. With respect to the first condition, namely, that they generate the same electromotive force, the real idea is to have the two or more machines contribute exactly the same pressure to the circuit. The necessity for this is obvious, the main reason being the same as in the case of two direct-current dynamos operating in multiple (or parallel). If the potential of one rose to be a little higher than the other, current of higher potential would flow into the circuit of lower potential, and in consequence one would operate as a motor. The necessity for the second condition being imposed is that a difference in frequency between one generator and another would tend to cause flickering in the lamps drawing their energy from such sources.

In fact, the true meaning of synchronism in this case is that the phase and frequency of one machine and another are identical. The alternating-current waves rise and fall in the same interval of time and in perfect unison when synchronism fully exists. The third condition, therefore, that the currents acting conjunctively in multiple must be in phase, is implied by the reference made to the frequencies. If the pulsations of power back and forth in the circuit were not in accord with one another, interference would result, even though the frequencies of each machine respectively were the same. Phase relationship is thus vital to synchronism, in that both the same frequency and perfect phase must be there simultaneously to guarantee good lighting.

Mechanism for Obtaining Synchronism.—The importance of securing synchronism in cases where single-, two-, and three-phase alternators respectively are coupled in parallel has led to the invention of means whereby differences in phase or voltage can be detected as described. The general principle involved is that of a device such as a lamp being employed in the circuit to detect changes of phase and voltage, and a switch to close the circuit when conditions are satisfactory in this respect. If, for purposes of illustration, two alternators are considered operating in parallel (Fig. 86), then the lamp and switch are placed in one leg of the circuit. The switch remains open, and the candle-power and fluctuations in the lamp are noted as follows: If one machine is producing a lower frequency and voltage than the other, the lamp will flicker. It will be alternately bright and dark. It will be bright when the difference in phase between one alternator current and the other is half a period. It will be dark when the potentials are equal and there is no difference in

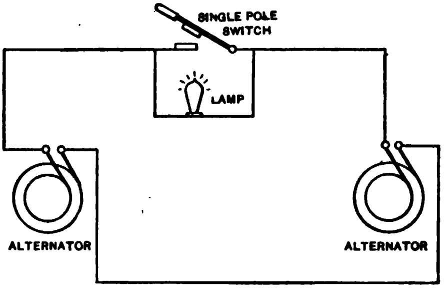


FIG. 86.—A Simple Single-phase Synchronizer.

phase. The flickering of the lamp will be more and more reduced as conditions become propitious. In other words, as the alternators approach perfect synchronism the effect is noticeable in the lamp, and very soon a point is reached where the switch may be closed. But perfect synchronism is not always attained, because of two conditions that may hide the true state of affairs. They are as follows: First, the lamp may be broken, and thus mislead the attendant; second, there may be a difference of from 15 to 30 volts between the two generators which is not discernible in the carbon filament. This latter state of affairs would mean, with the closing of the switch, a heavy flow of current from one machine to the other—the very condition that is to be avoided.

Synchronous Cross-connections. — Avoidance of the difficulty specified above is secured by means of a system of detection comprised in the following mechanism: A double-pole switch is used to break the circuit of both mains. Two lamps are connected across the circuit (Fig. 87) so that they bridge the break transversely, as shown in the illustration. The advantage of this method is found in it not only serving as a means of detecting differences of pressure and frequency, but because the lamps as thus connected will not rise to full illumination unless the currents are entirely in phase with each other. If the two phases are working in opposition, however, both sides of the circuit will have instants of equal potential, and in consequence the lamps will remain black. As the opposition of phase gives way more and more to an agreement in this respect, the lamps will begin to brighten, until, with a perfect unison of phase, the lamps appear at full candle-power. Just prior to this condition the double-pole switch in practice is closed, and the two alternators are in synchronism.

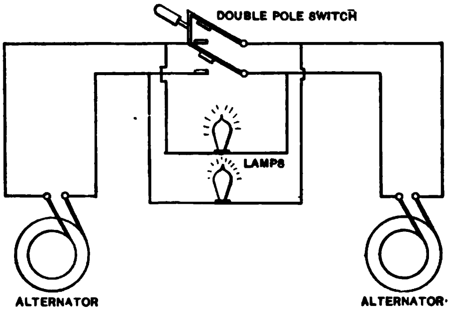


FIG. 87.—A Synchronizer with Lamps Cross-connected.

Synchronism with High-tension Alternators.— When the alternators produce pressures of many thousands of volts it is necessary to introduce modifications of the last plan (Fig. 88), and make use of transformers to eliminate danger as far as possible. This is done by means of two transformers, as shown in the illustration, so arranged that while their primary coils are connected in the customary manner to each alternator respectively, their secondaries are connected in series. A single lamp is placed in circuit with these secondary coils, as shown, and used as a detector of phase difference in the following manner: If the lamp flickers, the phases are not in unison with each other. If the lamp burns dimly, the phases are opposed to each other to a degree roughly corresponding to the difference in synchronism between the two machines. If the lamp burns with its normal brightness, then it is a sign that both alternators are in phase and the switch must be closed. The two secondary coils in this last instance must produce an aggregate pressure equal to that required by the lamp used as a "phase-difference" detector. If the lamp is a 115-volt one, then each secondary must develop by stepping down one-

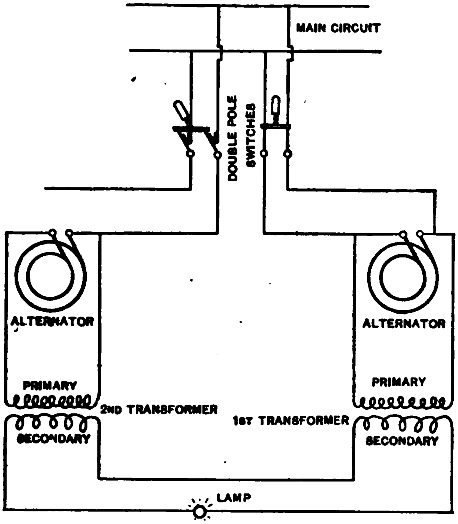


FIG. 88.—A Synchronizer for High-tension Currents.

half this pressure, or 57.5 volts. The transformers in this case are specially constructed for the purpose of securing a definite and reliable means of reaching synchronism.

Synchronism for Two- and Three-phase Alternators.—Alternators of two and three phase are also brought to synchronism by means which are based upon the principles outlined. The simplest plan, in the case of a three- or four-wire two-phase, as well as a three-wire three-phase system, is to insert a lamp and switch in each leg of the circuit (Fig. 89), and close the circuit according to the prescribed methods when synchronism is effected. The illustrations show the crystallization of this plan for a two- and three-phase system. In this instance the lamps may darken or brighten simultaneously, or

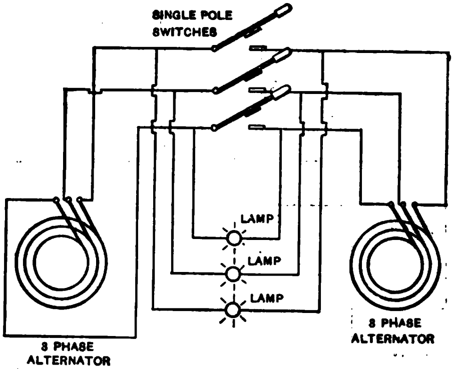


FIG. 89.—Three-phase Synchronizing System.

they may show this condition erratically. In such a case it will not be possible to secure synchronism until they operate alike. To attain this end the connections may have to be transposed, particularly when the lamps in a three-phase circuit light up successively. This is an indication of the fact that the main wires from one alternator do not connect to the correct poles on the other alternator. It will be necessary to transpose the wires until definite correspondence is secured, which is made evident by the simultaneous brightness and darkness of the lamps. Too much stress cannot be laid upon this point, as it is the simplest and best means of obtaining evidence of the correctness of the connections in polyphase circuits.

High-tension Polyphase Alternators in Synchronism.—Where the potential of the mains produced by the two- or three-phase alternators is very high, recourse is had to the use of transformers. Where a polyphase current is employed, it is evident that it consists of a series of distinct currents a certain interval behind one another. The circuit arrangement is simply a convenient adaptation of the wires to the currents, so as to avoid reactions and opposition between them. A single-phase transformer may be employed, therefore, in that part of the circuit in which but one phase is in action. Where two high-tension three-phase alternators are connected in parallel, a pair of single-phase transformers connected as shown (Fig. 90), with their secondaries in series with a single lamp, will represent an adequate means of ascertaining when synchronism is obtained. It is quite evident that if the connections between the two alternators are correct, then the electromotive force waves will rise in each simultaneously, and die out and reverse in the same manner. Any single phase of each, therefore, that corresponds to the other, will supply the means of examining the degree to which each is in synchronism with the other. For instance, if the waves are generated at the same instant, they will approach each machine in a manner described as follows: First, the first current or phase from each alternator rises and falls and reverses at the same instant; second, the second cur-

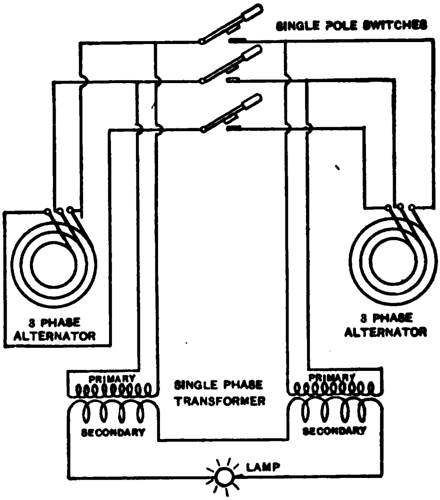


FIG. 90.—A High-tension Three-phase Synchronizer.

rent or phase from each alternator rises and falls and reverses at the same instant; third, the third current or phase rises and falls and reverses at the same instant. By this is meant that if a two- or three-phase current (Fig. 91) consists of two or three separate and distinct currents operating in the same general circuit, then, if perfect unison is established in each machine in an electrical sense, synchronism can be

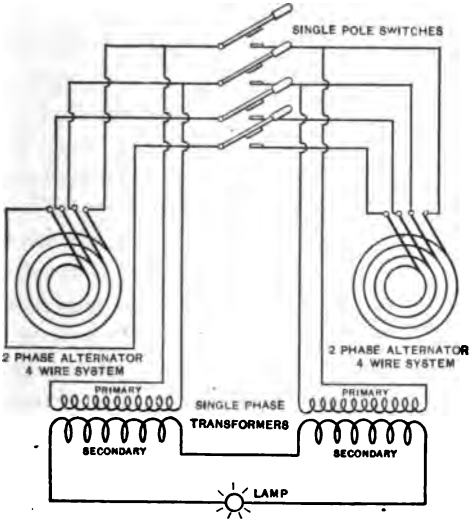


FIG. 91.—Two-phase High-tension Synchronizing System.

detected by an examination of the extent to which any two corresponding phases agree in this respect. A single-phase transformer connected as shown is therefore complying with these requirements, and will prove by the lighting of the lamp to full brightness that the machines are in phase, and by its dimness that the two waves or phases are acting in oppo-

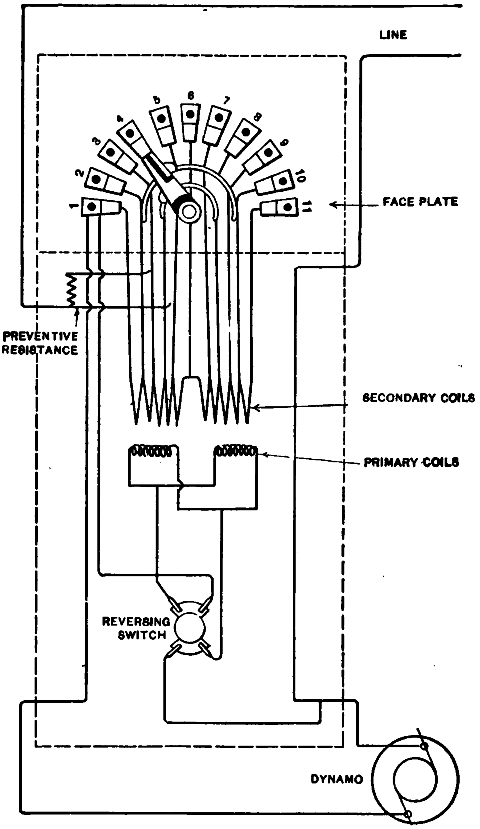


FIG. 92.—Connections of a Single-phase Regulator.

sition to each other, much or little according to the light.

Alternating-current Potential Regulators. — To quote from the manufacturers: "Whenever several feeders are receiving current from the same source of supply, it becomes necessary to provide means for adjusting the potential of each without disturbing the others. To accomplish this, potential regulators are employed. By means of one of these devices the potential of the feeder circuit to which it is connected may be accurately adjusted independently of the potential of the supply." Regulators for single and polyphase circuits are therefore employed to meet this exigency whose general design covers the following features: It possesses two coils, a primary and a secondary. The secondary is so constructed that it is adjustable by means of a switch. The regulator is therefore essentially a transformer (Fig. 92) whose secondary may be adjusted to give various electromotive forces within certain limits. The regulator (Fig. 93) is connected to the feeder circuit in such a manner that it can add to its pressure or subtract from it. The alternator may be the center of a system of feeders, some of which are more heavily loaded than others, and in consequence have more drop and less ultimate potential. Regulators installed to meet such circumstances will prove an indispensable element of service. If the potential of certain of these circuits is too high, it is lowered with a nicety of adjustment that provides an equalization of potential all round. Lamps drawing current from such sources are therefore able to burn with an equal candle-power with all variations of load.

Single-phase Motors.—To develop motive power from a single-phase current a form of mechanism is required which embodies certain of the necessary principles, if not all, that relate to the efficiency, durability, simplicity, and practical conditions of operation. The development of the single-phase motor is therefore a distinct problem, in that it prevents difficulties in the way of self-starting that cannot be overcome by ordinary forms of construction. For this reason it is necessary to itemize the typical methods in vogue, as they present characteristics calling for considerable interest and study in an

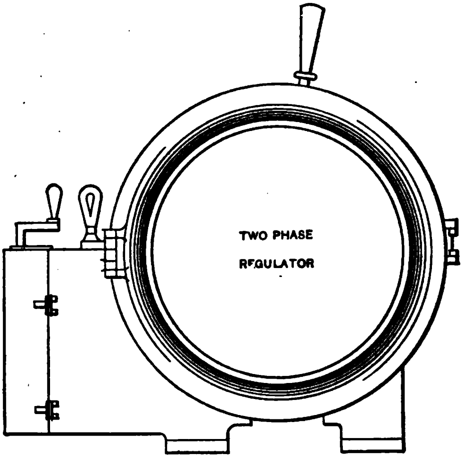


FIG. 93.—Appearance of a Two-phase Regulator.

analysis of this important problem. As far as the ordinary and most familiar type is concerned, namely the synchronous but not self-starting motor, it consists simply of an alternator which duplicates the features of the generator, and, therefore, after having been speeded up, will remain in step or synchronism. If overloaded, however, its speed not only drops, but the machine will cease turning, and be incapable of meeting the conditions of service to a further extent, unless started up by some external means, such as a gas-engine, a direct-current motor, or counter-shafting deriving its power from an independent source, like a steam-engine, water-power, air-pressure, etc.

Self-starting Single-phase Motors. — The self-starting single-phase motor is an object of great commercial interest, because its successful development along the strict lines of practice would mean a considerable reduction in the use of two- and three-phase currents. If the aim of engineering methods is that of greater simplicity, instead of further complications, then a simple and well-constructed single-phase self-starting motor of efficient operation would answer to this requirement in all particulars. At present there are two well-known types of self-starting single-phase motors: First, the induction motor; second, the series-wound motor. The induction motor is really a two- or three-phase motor, started from rest by means of a single-phase current (Fig. 94) which has been split up so as to reproduce temporarily the main features of a two- or three-phase current. In other words, the general method is to get the two- or three-phase motor up to speed by means of a doctored single phase and then cut out all but one phase, with which the motor runs, this being the only and true phase of the power circuit.

Making Two Phases from One Phase.—In practice two phases are obtained from one by a simple process. It is that of either accelerating or retarding part of the current, or the current in one circuit of the two-phase induction motor, by means of resistance or a condenser. The diagram shows the manner in which this is accomplished. The two circuits constituting the fields of the induction motor are indicated, so that it is clear that the current is either accelerated or delayed in one or the other of the two

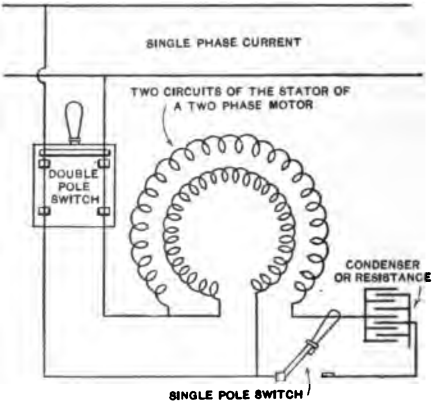


FIG. 94.—A Two-phase Induction Motor Connected to a Split-phase System and Operating with a Single-phase Current.

windings. The condenser in this case permits the current to enter the circuit to which it is connected the first, for the reason that the presence of capacity in an alternating-current circuit causes the current to advance before the electromotive force. There is therefore a lead in this circuit and, in comparison, a lag in the other. The lag in the other circuit, which has no condenser connected, is simply the lag ordinarily experienced in a circuit with the usual degree of inductance present. The formula for impedance, which makes it equal to

$$\sqrt{R^2+p^2\,L^2-\frac{1}{p\,K}},$$

must be considered, in which $R = $ ohms, $p = 2\pi \times$ frequency, $L = $ inductance in henries, and $K = $ capacity in microfarads, in order to arrive at a true determination of the correct value of the impedance in one circuit as compared with the other. By this method of artificially developing a two-phase from a single-phase current, the rotor will turn and rise to full speed. When this condition has been reached one of the circuits is cut out, so that the unaffected current from the dynamo operates directly, and the motor receives the single-phase current in but one of its two-field or stator windings.

Practice does not permit of a condenser being used in connection with large machines, for reasons of expense and space. Small motors may therefore be started with a condenser, as described, and larger ones with a coil or resistance. The technical name

" split phase " is descriptive enough to fully embody the meaning implied by its use in this system.

Single-phase, Series-wound, Self-starting Motor.—A direct-current series-wound motor means a motor in which the armature and field are in series, and therefore take the same current. In the illustration the path of the current is clearly shown (Fig. 95), both by diagram and in the ideal winding of a motor. The diagram shows the path of the current through both fields of a two-pole machine and through the armature. Both theory and practice show that *the reversal of the current in a series-wound motor will not*

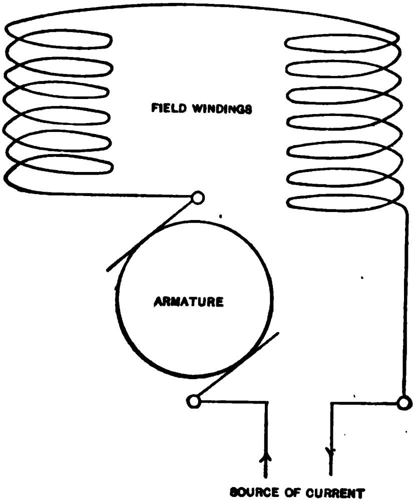


Fig. 95.—Principle of the Series-wound Motor.

change its direction of rotation. The windings of the series motor prove this upon examination, as may be noted as follows: If the current, entering according to the illustration (Fig. 96), develops a N and S pole in both the armature and field, then when current is reversed the N pole becomes S and the S pole becomes N in both the armature and the field. The pull existing between certain points of the arma-

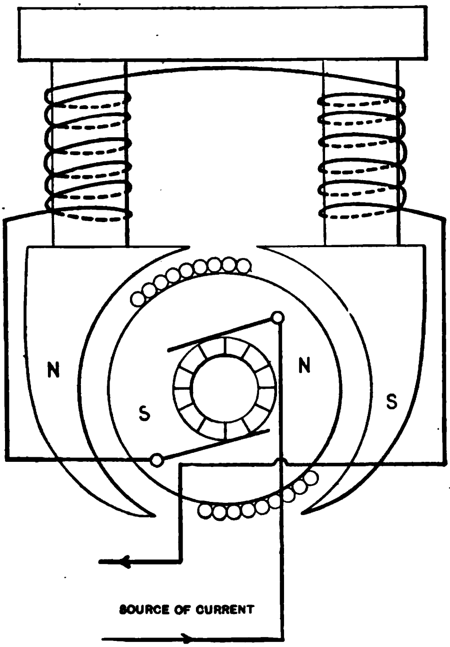


FIG. 96.—Windings of a Series-wound Motor, Showing the Poles, Due to the Armature Coils and Field when Causing Rotation.

ture and the field therefore does not change, even though the poles throughout mutually reverse when the current reverses. The arrow shows the general direction of rotation under these circumstances, a direction which evidently cannot change however rapidly the current alternates.

Defects of the Single-phase Series-wound Motor. —Unless the iron of a series-wound motor is laminated, the action of an alternating current will cause eddy currents and hysteresis. In addition, certain defects must be provided against which would be injurious to its service in actual practice. They may be considered under the following headings: First, excessive sparking at the brushes; second, too great a current when little or no load is on the machine; third, large size, because of certain features of construction which call for a bigger frame than for equal power with a direct current. The sparking at the brushes is due to the short-circuiting of the armature coils successively by the brushes. This occurs every time two-coil terminals or commutator segments pass a brush. The self-induction created in all of these coils develops a heavy current within them at the instant they are short-circuited as they rotate under the brushes. This is one of the chief causes of heavy currents within them, a feature difficult to eradicate in practice. A very heavy current in the machine at no load is due to the necessity of keeping the inductance low. The windings are therefore made as few as possible, with the consequence noted. The great torque or pull, is the one point which led to further experiments to develop such motor construction for practical purposes. The large size is due to the necessity of building it with a large air gap, in order to limit the sparking and hold the armature reaction in check. In consequence of the unusual air gap the pull is less, and a machine of greater dimensions is required to do the work than would otherwise be necessary. The lower the frequency the more nearly the conditions of direct-current service are approached, and the better the machine operates. At present the low frequency of from 16.666 to 25 cycles has given the best results. Motors, however, have been designed which showed such good results that their use for railway work seems well assured, according to published reports. Here a great starting torque is imperative, and any single-phase motor developing this feature must receive serious consideration as the prototype of others that will probably follow. A combination type of a series-wound and a synchronous motor has been developed and used in practice, built on the following lines: It consists of two machines in one, in that the armature and field have two windings: First, an armature winding connected to a commutator, through which all the characteristics of an ordinary direct-current armature are present; second, a winding connected to collector rings, through which all the features of the armature of a synchronous motor are present.

As far as the armature is concerned, it is therefore two armatures in one, with both windings superposed. The field also consists of two windings of the following nature: First, a winding of few turns and low resistance; and, second, a winding of many turns and high resistance. In other words, the machine is a series-wound motor with two fields which act separately on different occasions. It is also a single-phase synchronous motor with a separately excited field, in the sense that the commutator end is used for starting the motor (armature and low-resistance field in series), as though it were an ordinary series motor; and then when it is up to speed, the single-phase current is switched from the commutator to the collector rings. The current generated by the armature and passing out of the commutator is then led into the high-resistance field winding. The process, therefore, is composed of a series of interesting steps, which are given as follows:

First—Sending the single-phase current through the commutator and low-resistance field winding.

Second—When up to speed, cutting the current from the commutator and low-resistance field.

Third—Sending the current into the collector rings, thus converting the motor into a synchronous single phase.

Fourth—Sending the direct current generated by the armature from the commutator into the high-resistance shunt field winding. Thus the machine automatically supplies its own field excitation in the final stage of operation, and therefore represents a case of a synchronous single-phase motor with a separately excited field and a shunt dynamo operating conjointly. The motor is simply given full rotation by means of the series motor winding, and then becomes a synchronous alternator used as a motor.

Practical Connections of a Series and Synchronous Motor.—In the diagram (Fig. 97) the letters are sufficiently explicit to show the modus operandi. For instance, the power from the single-phase mains enters the switch through the fuses, arriving at the points lettered P for power. From these two points P P the power passes through the knife or blade of the switch to SM SM, or the series motor connections. If the two wires marked SM SM are traced down, it will be seen that the right-hand one goes to the upper brush and its power enters the armature, leaving by the lower brush to pass through the series field winding and thus back to SM on the left of the switch. In the present position of the switch the single-phase current runs the motor as a series-wound machine. Opening the switch cuts out these connections, and closing it above sends the power into C C, which, traced down, connect to the collector rings by the wires attached to them. By means of the switch handle the armature terminals A A from the commutator are connected to SF SF, the shunt field connections, which may be observed by tracing the wires leading from these points respectively.

Advantages of the Synchronous Motor.—In specifying the advantages of the synchronous motor, it is necessary to state that it will run at a constant speed unless overloaded to an extent that would slow down any other motor; with the difference, however, that

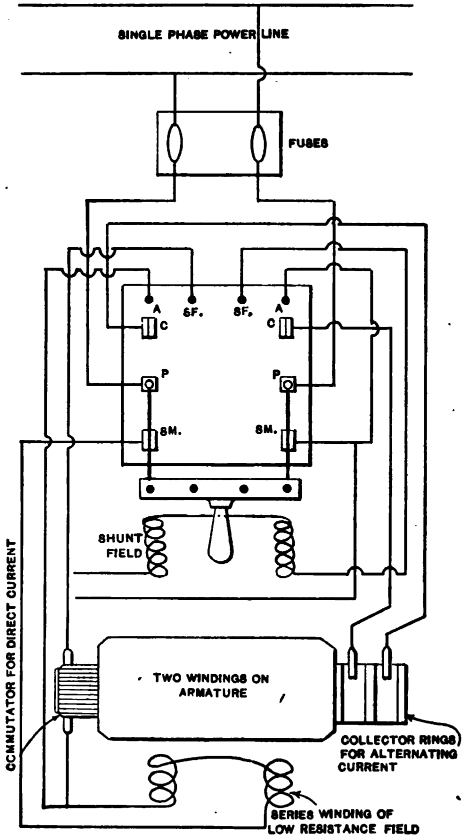

SINGLE PHASE POWER LINE
FUSES
A
SF.
SF.
A
C
C
P
P
SM.
SM.
SHUNT FIELD
COMMUTATOR FOR DIRECT CURRENT
TWO WINDINGS ON ARMATURE
COLLECTOR RINGS FOR ALTERNATING CURRENT
SERIES WINDING OF LOW RESISTANCE FIELD

FIG. 97.—Connections of a Single-phase Synchronous Motor.

in this case the synchronous motor comes to rest because it cannot gain synchronism if much behind. There are two- and three-phase as well as single-phase synchronous motors. These are self-starting, however, before their respective fields are in circuit, though no load is put upon them until they are in synchronism and their fields are in circuit. The advantage arising from the employment of synchronous motors of one, two, or three phase is found not only in their tendency to preserve a constant speed, but in the reaction they exercise upon the circuit to its benefit under certain circumstances. This reaction takes place when the fields are stronger than they should be. In this case the synchronous motor acts like a condenser; and, in consequence, in circuits where much inductance is present, it reduces it, and thereby increases the power factor. In other words, the synchronous motor, with a too powerful field, develops conditions which make the current in the power circuit lead in phase. This is very advantageous in reducing ϕ and thus increasing the value of cos. ϕ, it being remembered that $E \times C \times \cos. \phi = \text{watts}$, where $E =$ the amplitude of the E.M.F. and C the current. By increasing the power factor of the system, synchronous motors are therefore chosen in preference to induction motors where other devices present cause a marked inductive effect in the circuit.

Rotary Converters and Synchronous Motors.—The synchronous motor finds a broad application in the construction of rotary converters. These machines consist simply of a two- or three-phase alternator, whose armature winding connects to collector rings at one end (Fig. 98) and a commutator at the other end. Though such a machine can start itself, the heavy current it would draw from the mains has led to the practice of starting it by means of a small auxiliary induction motor before connecting to the alternating current. Under these circumstances it acts in every respect like a synchronous motor, developing a heavy torque only when fully up to its normal speed. It will then be ready to deliver the direct current for street-railway or other purposes.

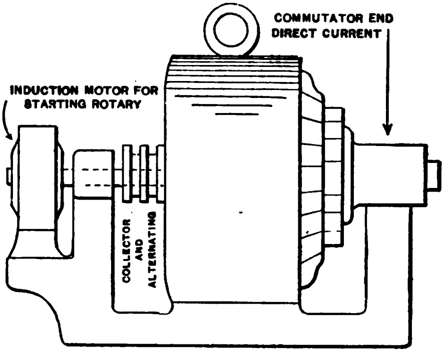


FIG. 98.—Rotary Converter with Induction Motor for Obtaining Synchronism.

CHAPTER X

PURPOSE OF TWO-PHASE GENERATION OF POWER.—THE TWO-PHASE ALTERNATOR.—ANGULAR SEPARATION OF A TWO-PHASE CURRENT.—WINDING OF A TWO-PHASE ARMATURE.—WEIGHTS OF WIRES WITH DIFFERENT PHASES.—A TWO-PHASE THREE- AND FOUR-WIRE SYSTEM.—TRACING A ROTARY TWO-PHASE FIELD.—COILS RECEIVING THE FIRST PHASE.—COILS RECEIVING THE SECOND PHASE.—COILS RECEIVING THE FIRST-PHASE REVERSED.—COILS RECEIVING THE SECOND-PHASE REVERSED.—TRACING A ROTARY THREE-PHASE FIELD.—ACTION OF THE FIRST PHASE.—ACTION OF THE SECOND PHASE.—ACTION OF THE THIRD PHASE.—THE REVERSING PHASES.

Purpose of Two-phase Generation of Power.—Power transmission has developed along the lines indicated by the application of two- and three-phase currents to motors operating by such forms of power. It necessarily involved the question of the generation of typical currents from machines whose chief peculiarity was to be found in the unique principles involved in their construction. In the single-phase generator these principles are clearly outlined. They embrace the central idea of an alternator producing a single-phase current, a current of electricity manifesting itself in the form of an electromotive force in combination with the current proper, and therefore, because of the singleness of the impulse or wave in each direction, deserving the title given—single phase. But a single-phase current, or single wave of power, to use a practical expression, requires either a synchronous motor to develop mechanical power from it, or a specially constructed motor of dual type, the idea of which is to provide a method of getting rotation by foreign means and then to throw in the single-phase current for power. For this reason the two- and three-phase currents are employed, because they provide a superior method of directly procuring rotation in an alternating-current motor of appropriate construction. Such motors are self-starting, if need be, or they may be synchronous; but, at any rate, they present a type which do not lose their power of rotation with changes of load — particularly overload — and are therefore fully reliable as efficient and steady power producers. The two-phase generation of power involves a system of alternator armature winding through which two distinct waves or impulses of electrical energy move back and forth through the circuit, one an appreciable instant of time behind the other.

The Two-phase Alternator. — In a reversal of Arago's rotations a means is found for the *production* of rotation in a horizontally supported copper disk (Fig. 99) by the rotation *above it* of a magnet. This rotation implied a rotating magnetic field, and the movement of the copper disk after it, the production of electric currents whose reaction, according to Lenz's law, resulted in the development of mechanical power. But in the two-phase alternator only two distinct alternating currents are produced, though the general principle underlying its construction clearly shows that three, four, five, or more may be generated. These particular currents, in this case two phase, are related to a particular system of power transmission and motor construction. A rotary magnetic field can be produced by them, and therefore an armature free to move, with short-circuited conductors, will follow the rotating field around in exactly the same manner as the rotations of Arago showed how the copper disk follows the

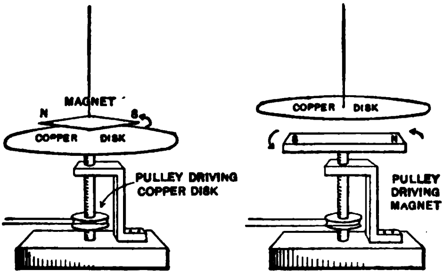


FIG. 99.

Rotation of Copper Disk Causing Rotation of Magnet Arago's Experiment.

Rotation of Magnet Causing Rotation of Copper Disk. Reversal of Arago's Experiment, Showing the Rotatory Field.

rotations of the magnet above it. But the construction of the two-phase generator, motor, and transformer, as well as that of the three phase, involves

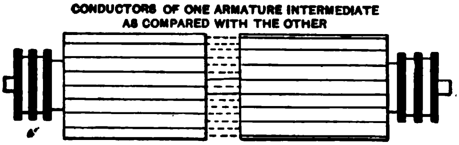

CONDUCTORS OF ONE ARMATURE INTERMEDIATE
AS COMPARED WITH THE OTHER

FIG. 100.—Two Single-phase Alternator Armatures with Conductors Set so as to Generate Two Distinct Phases.

technical details, the necessity for which appears in all departments of such practice.

If two distinct alternator armatures are mounted on one shaft, both armatures being identical in construction, and one is so set with regard to the other that the conductors of one are a little in advance (Fig. 100) of the other, and two distinct fields of an equal number of poles are placed side by side and the armatures set within them, then the following conditions exist when the armatures are rotated: First, one armature will send through its two connecting wires a single-phase current; second, the other armature will send through its two wires a single-phase current; third, the two single-phase currents follow one another, because they have not been produced simultaneously as regards their electromotive forces; fourth, both currents considered collectively constitute a case where the total energy is developed in two phases, separated to a greater or less extent at the option of the designer.

Angular Separation of a Two-phase Current.—The degree of separation between the electromotive forces, though it may be made greater or less according to the position of the two armatures, is set by theory and practice at 90 degrees. By this is meant that when a conductor on one armature is under the middle of a given pole piece (Fig. 101), a corresponding conductor on the other armature is lying between a corresponding pole of the second field and the next that follows. To be more explicit, a 90-degree difference of phase between the two currents implies that when a conductor of one armature is under the middle or a north pole, a corresponding conductor on

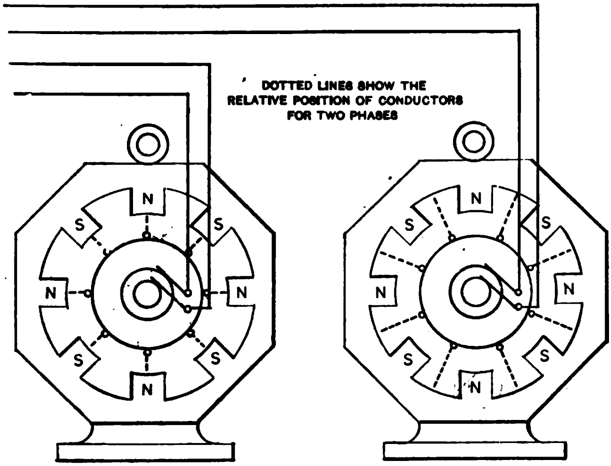

DOTTED LINES SHOW THE RELATIVE POSITION OF CONDUCTORS FOR TWO PHASES
N
S
S
N
N
S
S
N
N
S
S
N
N
S
S
N

Fig. 101.—Two Single-phase Alternators, Direct-connected, Producing a Two-phase Current.

the other armature lies midway between a north and a south pole. This would mean that the two armatures are so placed on the shaft with regard to each other that their corresponding conductors occupy respectively these positions with regard to the poles of the field. On this basis it becomes quite evident that when the corresponding conductors of the two armatures are generating electromotive force, one set are generating a maximum E.M.F. when the other set are generating a minimum E.M.F. It is this idea, therefore, which is involved in the principle of construction—the idea that the two currents, though

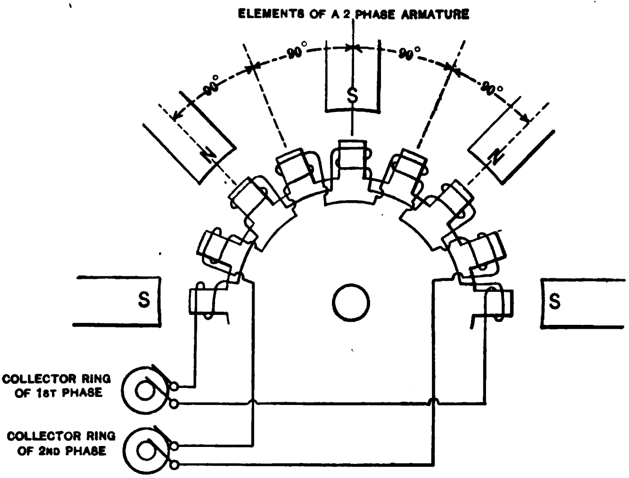

ELEMENTS OF A 2 PHASE ARMATURE
90°
90°
90°
90°
N
S
N
S
S
COLLECTOR RING OF 1ST PHASE
COLLECTOR RING OF 2ND PHASE

Fig. 102.—Part of a Two-phase Alternator, Showing General Principle of Armature Connections with a 90-degree Difference in Phase Between Them.

distinct in themselves, are only separated from each other to an extent which permits one E.M.F. to be at its highest when the other E.M.F. is at its lowest. Though the representation of this is generally made by an angular difference of 90 degrees, it may be readily understood as a 90-degree difference only with respect to the pole pieces (Fig. 102), two of which constitute 360 degrees from the middle of their neutral spaces on either side. The fact that two such armatures as described are superposed, and in the same manner the two fields, does not in any way affect the fundamental principle involved. In actual practice these last conditions are necessary, and the two-phase alternator therefore possesses only one armature and one field as built for the generation of two-phase currents for transmission, power, and lighting.

Winding of a Two-phase Armature.—The fact that such an armature must be wound with two sets of conductors, so situated respectively that when one set lies beneath the middle of the pole arc the other set is midway between the pole tips, simplifies the winding proposition. The conductors of both sets, for instance, are wound according to what is called the wave form of winding. By this is meant that the conductors are placed in the slots and wound from the front to the back, then across the back a certain distance to certain slots and brought forward, then across the front to certain slots and brought backward, etc. If the cylindrical armature surface is laid out flat it assumes the appearance of a rectangle. If the slots are indicated upon it (Fig. 103), and the back-and-forth direction of the winding traced, a wave will be discovered from which the name was derived, which typifies the style of winding. One set of conductors, lying beneath the middle of the arc of the pole pieces wound according to the wave

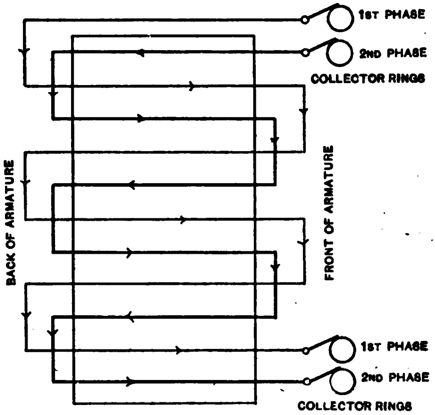


FIG. 103.—Development of an Alternator Armature of Six Conductors per Phase, Showing the Two-phase Winding and Connections.

method, would necessarily terminate in two collector rings. From these two collector rings two main wires connected to the brushes pressing upon them lead out as the first two supply wires. The other set of conductors, which, with respect to the position of the first set, lie in the neutral spaces between the poles, are also wound in the same manner as the first. In fact, the two sets of conductors always found upon the armature of a two-phase machine are replicas of each other, perfectly identical in manner of winding and number of turns, though they differ in position on the surface of the armature. The second set of turns also end in two collector rings, to which the two ends of this winding are connected. From the two brushes pressing upon these two collector rings a separate single-phase current issues. To the two brushes specified a separate pair of mains are connected, and the current from them is used in conjunction with the current obtained from the two connected to the collector rings of the first winding.

Though four wires are employed to conduct two-phase power, through which the title *two-phase four-wire system* originated, it is possible to so connect the four wires that, without any ill results following as regards the two-phase power, only three wires become necessary, thus originating the title *two-phase three-wire system.* Three collector rings may also be employed instead of four (Fig. 104), provided one of the rings is used as a common connection for the two armature windings. General practice, as found crystallized in the machines constructed by the leading manufacturers, calls for the use of four collector rings on two-phase alternators. The diagrams of one- and two-phase armature windings show in a comparative sense the similarity and difference between them. Taken separately, they yield on analysis the same elements; that is, the two-phase winding is seen to be composed of two individual windings (Fig. 105), either of which is the same as that of the single-phase machine. The difference between them, consequently, is simply that of a single wave being produced from the single phase, and the two waves following each other being produced from the two phase, the element of time between the last-mentioned waves being entirely a question of the relative positions of the conductors with regard to each other and the poles they pass under.

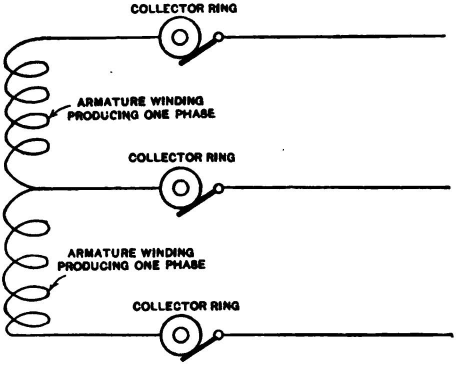

COLLECTOR RING
ARMATURE WINDING PRODUCING ONE PHASE
COLLECTOR RING
ARMATURE WINDING PRODUCING ONE PHASE
COLLECTOR RING

FIG. 104.—Principle of a Three-wire Two-phase System of Connection.

Weights of Wires with Different Phases.—The single-, two-, and three-phase systems of generation and transmission require different methods of connecting up. The single-phase system is one which may be applied to lighting and power distribution with either two or three wires. If two wires are used, the ordinary system is involved. If three wires are employed, a system similar to that utilized for the distribution of direct current, commonly called the three-wire system, is presented. The two-phase system may be used as a three- or four-wire installation. If a four wire, it is really equivalent to that found in two single-phase systems. If a three-wire system, it means that the third wire is being used as a common return for the other two. The three-phase system involves the use of either three

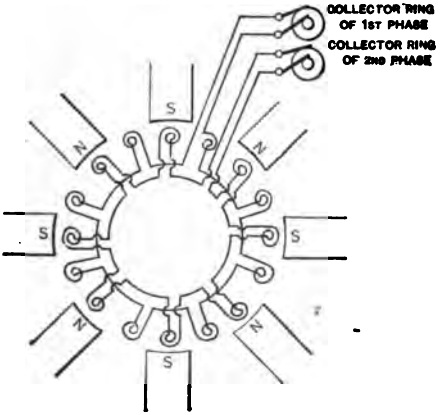


FIG. 105.—Windings of a Two-phase Alternator Consist of Two Sets of One-phase Conductors.

wires in the so-called mesh or delta (Δ) system, or four wires as found in the so-called star or Y system. In the last case, namely, where the Y connection is used, a wire is run from the extremity of each point of the star and one from its common junction. The various relative weights of wires for equal power, drop, and pressure have been estimated by Georges in a paper published by the *Elektrotechnische Zeitschrift* and are as follows:

WEIGHT OF MAINS FOR SINGLE-, TWO-, AND THREE-PHASE SYSTEMS.

Single-phase, two wires	100.00
Single-phase, three wires (assuming the third wire to be one-half the cross-section in circular mils of the others)	31.25
Two-phase, four wires	100.00
Two-phase, three wires (the voltage being measured between the lines and the common return)	72.80
Three-phase, three wires (mesh)	75.00
Three-phase, four wires (a neutral wire from the common junction)	29.20

A Two-phase Three- and Four-wire System.—Where four wires are employed, a two-phase system is simply a double single phase, and in consequence there is no saving in copper as far as the transmission of an equal amount of power in both systems is concerned. If a three-wire system is employed, in which one of the wires serves as a common return, then the pressure is calculated by the following method between each wire and the common return: Calling P the pressure between each wire and the common return, the pressure between the two main wires is the square root of $2 \times P = \sqrt{2} \times P$. For instance, if the pressure between one of the main wires and the return is 1,000 volts, then the pressure between the two mains is

$$\sqrt{2} \times 1{,}000 = 1.41 \times 1{,}000 = 1{,}410 \text{ volts.}$$

In the following table the figures are given which represent the voltages found between the two mains of a two-phase three-wire system, when the voltage between them respectively and the common return is as given:

TABLE OF VOLTAGES BETWEEN MAINS IN A TWO-PHASE THREE-WIRE SYSTEM.

Pressure between mains and return.	Pressure between mains.
1,000 volts	1,410 volts
2,000 "	2,820 "
3,000 "	4,230 "
4,000 "	5,640 "
5,000 "	7,050 "
6,000 "	8,460 "
7,000 "	9,870 "
8,000 "	11,280 "
9,000 "	12,690 "
10,000 "	14,100 "

The problem which presents itself in connection with both two- and three-phase systems is the amount of copper required by each system to transmit equal quantities of power at equal efficiencies.

Tracing a Rotary Two-phase Field.—The generation of the electromotive forces and corresponding currents in a two-phase alternator presents no such difficulty to the imagination as that of tracing up in detail the magnetic poles which appear in different parts of an iron ring, wound with appropriate coils, and apparently producing a rotating field. The poles appearing in the iron ring sweep around as though rotation in a magnetic sense actually occurred, when in fact this impression is only conveyed through the systematic appearance of the poles in various parts of the iron ring. If the appearance of these poles is traced around, it is not difficult to see how rotation will ensue in consequence, of any metal mass, free to turn under their influence. If a ring of laminated wrought iron is wound with four coils, two in the vertical and two in the horizontal plane, and they are so wound that one phase can operate in the horizontal pair of coils and produce two consequent poles, and the other phase can operate on the vertical pair of coils and produce two consequent poles, then a series of such actions can be explained as follows:

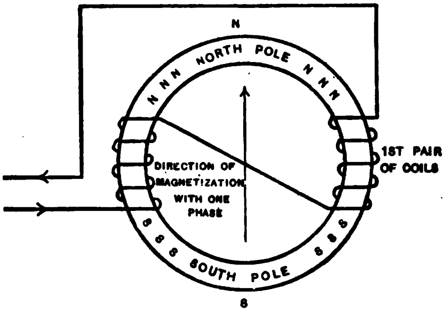


FIG. 106.—Influence of the First Phase Upon the Stator, Showing Positions of the N and S Poles.

Coils Receiving the First Phase.—The coils in the horizontal plane receiving the first phase of current must be so wound that the current passing through them produces in each coil a north pole at its upper end and a south pole (Fig. 106) at its lower end. The arrow clearly shows the positions the north and south poles of the ring occupy. What are called consequent poles, or poles produced by the co-operation of two or more magnets, are thus in evidence in this consideration of the effect produced in the stator of a two-phase induction motor by the winding of two coils receiving the first phase of the alternator. The coils as illustrated are 90 degrees apart, showing that when the current is at its maximum in the coils referred to the current is at its minimum, or just about to begin, in the second pair of coils. It must be remembered that the current or phase in the second or, in this case, vertically situated pair of coils will flow in the same direction as that of the first impulse or phase. There will be sufficient *time* between them, however, to permit the current in the first pair of coils to reach its highest point before that in the second pair begins to flow.

Coils Receiving the Second Phase.—The current which begins to flow in the second pair of coils, as shown in the second illustration (Fig. 107), is therefore increasing in strength at the very moment the current in the first pair of coils is decreasing in strength. The north-pole effect, therefore, to the right of the upper coil in the second illustration is increasing in strength, but that to its left is decreasing in strength. Thus, to all appearances, the strength of the north pole, as produced by the first phase in the first pair of coils, seems shifted to the right by the effect of the second phase of current in the second or vertically situated pair of coils, and by the fact that the magnetizing power of the first pair of coils in the first sketch is falling to zero. When the current in the first pair of coils does fall to zero the current in the second pair of coils has reached its greatest strength, and therefore there is only a north-pole effect present, due to the second pair of coils. It will be noted that the north pole has definitely shifted its position, as well as the south pole, from a vertical to a horizontal one. The arrow in the first and second sketch will show the manner and extent to which this change of position of the

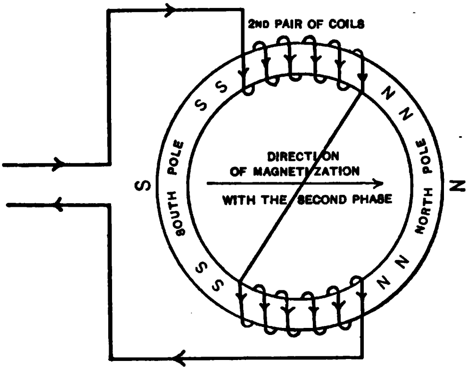


FIG. 107.—Influence of the Second Phase Upon the Stator, Showing Positions of the N and S Poles.

north pole has occurred. The shifting, therefore, as far as these two sketches are concerned, due to the rise and fall to zero of the first phase and the rise to its greatest value of the second-phase current, is just 90 degrees.

Coils Receiving the First-phase Reversed.—When the current in the second pair of coils has reached its highest value, due to the second phase having reached its maximum, the first phase is ready to act in a reverse direction. The current of the first phase is therefore reversed and rising in value when the current in the second pair of coils begins to fall to zero. This reversed current of the first phase is now operating in the first pair of coils over again, and it is necessary to a complete understanding of this action to grasp the meaning of the effect of this reversal of current in the first pair of coils upon the position of the north pole.

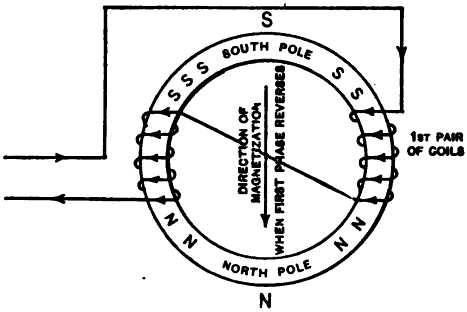


FIG. 108.—Influence of the First Phase Reversed Upon the Stator, Showing Positions of the N and S Poles.

The third illustration (Fig. 108) shows the first pair of coils traversed by a reversed current. The pole effect produced by this is also depicted with the north pole now at the lower part of the ring, the arrow showing the position of the field. The current in the second pair of coils is diminishing, and is flowing in an opposite direction to that flowing in the first pair. Therefore, in the third illustration it will be noted that the current does not enter by the left-hand coil, but by the right-hand one. The connections and coils remain the same, but the current by reversing in them produces a N and S pole in opposite positions in the ring. The north pole is now below instead of above, and the north-pole effect at the right-hand side of the ring diminishes rapidly, due to the reduction of current in the second pair of coils. By the time the N-pole effect, produced originally by the second pair of coils, has fallen to zero, the N-pole effect of the first pair of coils, now carrying a reversed first-phase current, has reached a maximum. Tracing the current in the third illustration will clearly show why the N pole and the S pole have shifted from their former position to those indicated by the arrow. Reviewing the series of positions the N pole has occupied, the different sketches show its successive changes from the first position in the upper part of the ring around toward the right until it has, as far as the analysis has gone, reached a position in the lower part of the ring.

Coils Reversing the Second-Phase Reversed.— The reversed current of the first phase, having reached its highest value, begins to diminish in strength. But at the same instant the second pair of coils begins to receive the reversed current of the second phase. This reversed current of the second phase increases in strength, and the reversed current of the first phase diminishes in strength. The N pole therefore begins to shift its position of greatest strength from the lower part of the ring to a new position to the left of this. The current ultimately falls to zero in the first pair of coils, and then the current in the second pair has reached its greatest value.

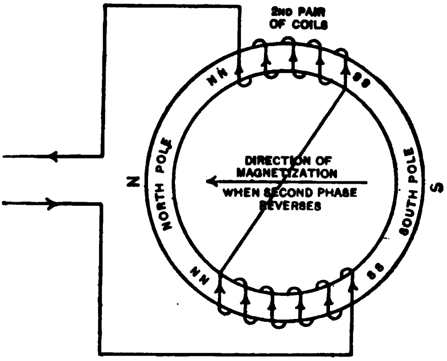


FIG. 109.—Influence of the Second Phase Reversed Upon the Stator, Showing Positions of the N and S Poles.

Examination of the fourth illustration (Fig. 109) will show that when this condition of affairs exists only the second pair of coils, carrying the reversed second phase, are in full operation, and the N pole has in consequence been shifted from the lower part of the ring to the left-hand side, as shown. From this point on the cycle begins again as it did in the first place, and the current, dying away in the second pair of coils, co-operates with the first phase, which grows in strength in the first pair of coils, to shift the full strength of the N pole from the left-hand position to the upper part of the ring, as shown in the first illustration of this series. The complete cycle of operations therefore results in the apparent rotation of the magnetic field (Fig. 110), but not in the sense that might be popularly accepted. It might be better understood as a systematic development of a N and S pole, respectively, at the extremities of a diameter that describes a circle of the same dimensions as the ring.

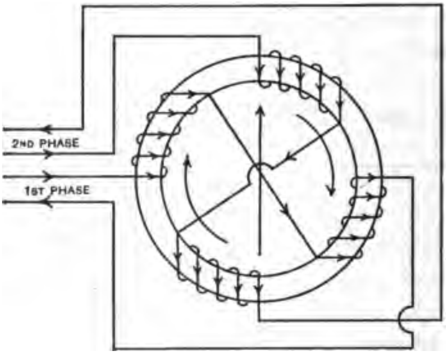


FIG. 110.—Complete Circuit of the Field or Stator of a Two-phase Induction Motor, Showing Circuits of the Two Phases.

Tracing a Rotary Three-phase Field.—The principles applying to the production of a two-phase rotary field do not differ essentially from those which may be regarded as essential in the production of a three-phase rotary field. The difference consists mainly in the fact that instead of two distinct impulses, phases, or waves of current one following the other at a fixed interval the phases are three in number, and 120 degrees apart instead of only 90 degrees. The conditions thus produced necessitate the use of three instead of two or four coils wound around a laminated wrought-iron ring. If the case of three coils around a ring is presented, then the three phases of current may be successively examined with respect to the positions of the poles and character of the connections employed.

Action of the First Phase.—The simplest manner in which the development of a rotary field can be explained is by illustrating the stator (Fig. 111) as a laminated wrought-iron ring wound completely around with a closed coil. The three-phase current which is to be used to develop the field consists of three distinct waves of electromotive force and current. In consequence, it is necessary to provide three separate circuits for the current. These circuits, as previously explained, may be connected up in the Y or Δ fashion, a wire being run from either the points of the Y or the points of the Δ. The latter is called the mesh connection, and on examination will show its similarity to a closed coil as illustrated, provided a top connection is made at three points 120 degrees apart in the coil. This idea is represented in the illustration (Fig. 112), showing the three wires which divide the coil up into A, B, and C coils, or a three-part coil. The first phase of current enters at *a* and passes downward through the A and B coils

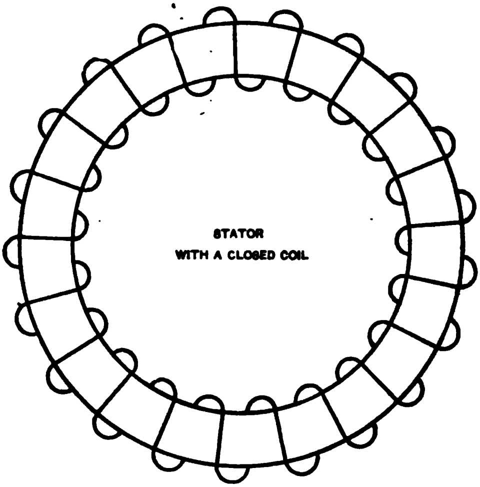


FIG. 111.—Elements of the Field of a Three-phase Motor.

to the points *b* and *c*, from which it passes out as shown by the arrows. During its downward path through the A and B coils it may be noted that the current in the right-hand coil circulates in such a direction that it produces a S pole above and a N pole below. This may be proven by tracing the direction of the current in this instance as in that of the left-hand or A coil, which also produces a S pole above and a N pole below. The current of the first phase, therefore, enters at *a* and leaves at *b* and *c*, which act as returns. There are thus a north and a south pole produced which originally moved from the positions shown by the dotted line subtending an angle of 120 degrees. These, then, may be assumed as the first definite positions the N and S poles will assume due to the first phase before its reversal.

Action of the Second Phase.—The action of the second outward phase of current is clearly shown on this basis (Fig. 113) by the current entering at *b*. The same phenomenon may be traced by following the current through the B and C coils until it finally passes out at *a* and *c*. Both the B and C coils co-operate in producing a consequent pole at S, and a north pole at N. The needle indicates the extent of the swing around of the N pole, an angle equal to 120

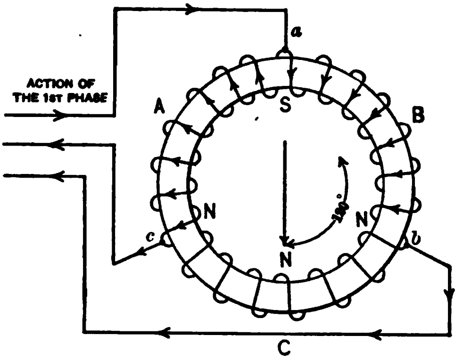


FIG. 112.—Position of N Pole Due to the First Phase.

degrees. Though the first phase completes its forward action through *a* and the A and B coils, it must be remembered that there is still its reverse wave to consider, though the consideration of this does not materially affect the principle outlined by the flow forward of the three phases successively before they reverse. For this reason the third phase can be considered as following the second at a certain interval, equal, of course, to the same interval which elapses before the second phase followed the first.

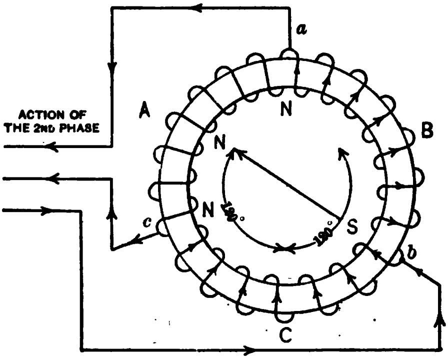


FIG. 113.—Position of N Pole Due to the Second Phase.

Action of the Third Phase.—According to the diagrams, the first phase entered at *a*, the second at *b*, and necessarily the third must enter at *c*. When this occurs the A and C coils develop together consequent poles at S and N. The action as thus outlined shows inactivity when the first phase enters at *a*, of the C coil; inactivity when the second phase enters at *b*, of the A coil; and, finally, inactivity when the third phase enters at *c*, of the B coil. The reversing current of each phase has not as yet been considered, but it is evident that if the reverse current of each phase acted in a manner detrimental to the proper economy of the system, this method of power production would fall into disuse. The action of the current of the third phase, according to the illustration (Fig. 114), is to swing the N pole around to the position indicated, which position is the one from which the N pole originally started, as shown by the dotted line in the sketch illustrating the action of the current of the first phase.

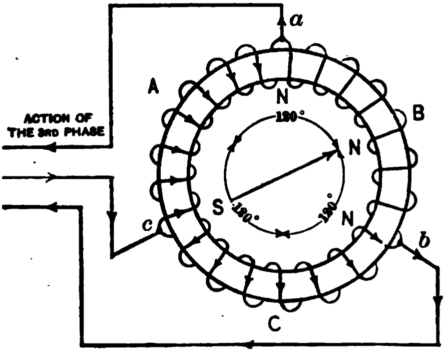


FIG. 114.—Position of N Pole Due to the Third Phase.

The Reversing Phases.—Perhaps the most desirable way to look upon the crossing phases is to consider them in succession, as follows: The reversing first phase, which must pass out of *a* before the second phase has reached its maximum in *b*; the reversing second phase, which must pass out of *b* before the third phase has reached its maximum in *c*; the reversing third phase, which must pass out of *c* before the first phase has reached its maximum in *a*. The waves of E.M.F. show that the difference between them is 120 degrees. By tracing the separate phases or waves it will be discovered that the first phase has passed its maximum strength by 30 degrees when the first phase begins to grow. Thus the rising second phase and the falling first phase cross each other, and the first phase reaches zero a little before the second phase reaches its maximum. The first phase, therefore, has reversed before the second phase reaches its maximum, and the second phase, therefore, can operate in the C and B coils and pass out at *a* and *c*, as indicated, along with the reverse first-phase current. A further examination of the current or E.M.F. waves of a three-phase system will show similar conditions existing with respect to the second and third phases, and then at the beginning with respect to the third and first phases.

CHAPTER XI

EXAMINATION OF THE THREE SINE WAVES.—THE FIRST PHASE FORWARD.—THE FIRST PHASE REVERSED.—THE SECOND PHASE REVERSED.—THE THIRD PHASE REVERSED.—TRACING THE PHASES IN THE CIRCUITS.—MORE CURRENT IN ONE MAIN THAN ANOTHER.—GENERATING A THREE-PHASE CURRENT.—THE THREE-PHASE GENERATOR.—THE THREE ARMATURE WINDINGS.—A SIX-WIRE THREE-PHASE SYSTEM.—A FOUR-WIRE THREE-PHASE SYSTEM.—TWO PHASE WITH THREE MAINS.

Examination of the Three Sine Waves.—An examination of the three sine waves of a three-phase current shows the relationship existing between the points of equal E.M.F. or current in any two waves and the third wave. An analysis of a three-phase current also shows the existence of not only three electromotive forces, but three currents as well, each separated from its corresponding E.M.F. by a slight lag. The analysis would follow along the lines indicated:

The First Phase Forward.—Starting from either a maximum or a minimum or zero point in the line, it rises to a maximum and then drops to zero in the two upper coils of the three-phase field. This means, according to the illustration (Fig. 115), that whatever polarity these two coils develop, they develop it from zero to a certain high value, and then again reach zero, as far as their co-operative effect is concerned in producing the pole referred to. The inflowing first phase then ceases, as far as these two upper coils are concerned. But the reverse first phase now must operate, according to the conditions existing in the three-phase armature, in virtue of which three independent currents are first sent out 120 degrees apart; and only 180 degrees after the first phase has begun to operate in the two upper A B coils, the reverse current of the first phase makes its appearance. The following table may therefore be drawn up for the purpose of keeping these conditions clearly in mind:

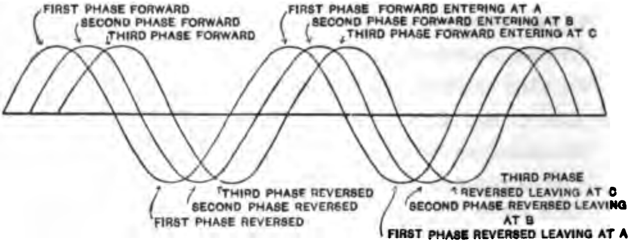

FIRST PHASE FORWARD
SECOND PHASE FORWARD
THIRD PHASE FORWARD
FIRST PHASE FORWARD ENTERING AT A
SECOND PHASE FORWARD ENTERING AT B
THIRD PHASE FORWARD ENTERING AT C
THIRD PHASE REVERSED
SECOND PHASE REVERSED
FIRST PHASE REVERSED
THIRD PHASE REVERSED LEAVING AT C
SECOND PHASE REVERSED LEAVING AT B
FIRST PHASE REVERSED LEAVING AT A

FIG. 115.—Three Phases Forward and Reversed, as they Enter and Leave the Coils.

NUMBER OF PHASE FORWARD.

First lasting through 180 degrees.
Second lasting through 180 degrees.
Third lasting through 180 degrees.

NUMBER OF PHASE REVERSED.

First lasting through 180 degrees.
Second lasting through 180 degrees.
Third lasting through 180 degrees.

DISTANCE BETWEEN PHASES.

Third and first, 120 degrees.
First and second, 120 degrees.
Second and third, 120 degrees.

The First Phase Reversed.—The table clearly shows that the first phase forward, only lasting through 180 degrees, then begins to reverse, though while it was approaching zero, and of course before reversing, the second phase forward had begun. An examination of the sine-wave curve shows the intersection of the rising second-phase sine wave of current and the falling first-phase sine wave of current. The falling sine wave of the first phase, as previously stated, is denuding the two upper coils of current, and will have left them almost entirely, when the second phase begins in the B and C coils and magnetizes them with increasing power. But after the points of equal value in the first and second phases have met, the one falls to zero and the other rises to a maximum.

The first phase falls to zero, and then begins to grow in strength in a reverse direction, as indicated in the illustration. A reverse current flowing through the *a* conductor means a reverse pole, instead of the one formerly there. The one originally there, due to the forward current of the first phase, was a S pole.

The reverse current therefore produces a N pole a short time after the second phase has been operating in the *b* conductor and in the B and C coils. This reversal of the first phase acts in such a manner that the S pole produced by the second phase is augmented in strength. Not only is this consequent S pole strengthened, but a consequent N pole of growing strength also appears, due to the effect of the reversed first phase in the A and B coils. The reversed first phase reaches a maximum an instant after the forward second phase reaches its greatest value. This means, as far as these currents are concerned, that the N-pole effect due to the reversed first phase grows a little more slowly than the S-pole effect due to the second forward phase. But the important fact that the polarity originally produced in the A and B coils by the first-phase current died away and was replaced by a growing N pole, and that the polarity produced by the second phase replaced the N pole originally at *b* by a S pole, shows the manner in which the S pole, originally operating at its maximum at *a*, swings, or apparently rotates around, a distance equal to 120 degrees, and then operates at a maximum at this point in the same manner as at the point marked *a*.

The Second Phase Reversed.—A further analysis with respect to the second phase of the current shows that it reverses just before the third phase rises to its maximum. This means that the S pole the third phase will develop will not gain its greatest strength until an instant after the reversed second phase begins to operate. The reversed first phase has reached its maximum a little before the second phase begins to reverse. This presents the situation, therefore, of the reversed first phase beginning to die away, that is to say, its effect in producing a N pole diminishing at *a*, just before the effect of the forward second phase at *b*, which was producing a S pole, falls to zero; and this, in its place, occurring just before the third phase flowing forward rises to its maximum value in the A and C coils. When the second phase reverses, its growing strength at *b* produces a stronger and stronger N pole. This N pole, however, does not begin to grow until the S pole due to the forward second phase has fallen to zero. As shown by the analysis, and as indicated in the illustration of the three phases of current (Fig. 115), the point of reversal of the second phase lies between the maximum of the reversed first phase and the maximum of the forward third phase. In fact, it is clearly evident from the illustration that the maximum strength of the forward second phase is reached at the same instant that the reversed third phase falling to zero and the reversed first phase rising to its maximum cross each other. Or the statement may be made with reference to the maximum value of the reversed first phase, that at this instant the rising third phase forward and the falling second phase forward cross each other. The reversed second phase, however, produces a N pole of growing strength in place of the S pole developed there an instant before by the forward second phase. This means a further shifting of the N pole from its position of greatest strength at *a* to a new position of greatest strength at *b*. The shifting is now caused by the reversed first and second phases in co-operation with the forward third phase. Through this it appears as though the N pole rotated around in the ring from the *a* to the *b* position.

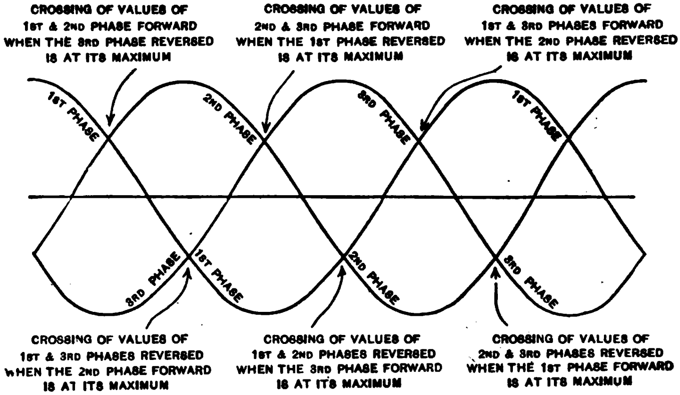

CROSSING OF VALUES OF 1ST & 2ND PHASE FORWARD WHEN THE 3RD PHASE REVERSED IS AT ITS MAXIMUM
CROSSING OF VALUES OF 2ND & 3RD PHASE FORWARD WHEN THE 1ST PHASE REVERSED IS AT ITS MAXIMUM
CROSSING OF VALUES OF 1ST & 3RD PHASES FORWARD WHEN THE 2ND PHASE REVERSED IS AT ITS MAXIMUM
1ST PHASE
2ND PHASE
3RD PHASE
1ST PHASE
3RD PHASE
1ST PHASE
2ND PHASE
3RD PHASE
CROSSING OF VALUES OF 1ST & 3RD PHASES REVERSED WHEN THE 2ND PHASE FORWARD IS AT ITS MAXIMUM
CROSSING OF VALUES OF 1ST & 2ND PHASES REVERSED WHEN THE 3RD PHASE FORWARD IS AT ITS MAXIMUM
CROSSING OF VALUES OF 2ND & 3RD PHASES REVERSED WHEN THE 1ST PHASE FORWARD IS AT ITS MAXIMUM

FIG. 116.—Relative Positions of Each Phase.

The Third Phase Reversed.—The general proposition remains the same with respect to the reversal of the third phase. When the third phase flowed forward in the A and C coils, it produced a S pole. But the S pole in this case was situated opposite to a N pole on the other side of the ring. The reversal of the third phase, however, cannot occur until the forward third phase has died out. The forward third phase reaches its maximum value (Fig. 116) a little after the forward second phase passes its zero value and begins to reverse. But the forward second phase crosses the zero line and begins to reverse only a little after the reverse first phase has reached its maximum value. Therefore, when the third phase begins to reverse, the reversed second phase has passed its maximum value and is approaching zero. This means that the N pole produced by the reversed second phase operating at *b* is rapidly diminishing in strength, and that a new pole is being produced at *c* by the reversed third phase operating at that point. This new pole produced at *c* is the reverse of that developed by the forward third phase. The forward third phase developed a S pole which rose to a maximum value, and thus fell away in strength to zero, with the rise and fall to zero of the forward third phase. The reversed third phase produces a reverse pole, in this case a N pole of growing strength. The N pole has shifted, therefore, through the action of the reversed first-, second-, and third-phase currents, from its position at *a* to a new position at *b*, and now finally to *c*. The reversed second phase is at its maximum value after the current of the first phase begins to rise and flow forward, and before the current of the forward third phase falls to zero. The current of the reversed third phase is at its maximum value at the same instant that the rising and forward second phase crosses the falling and forward first phase. This means that when the reversed third phase is acting at its best in producing a N pole of greatest strength at *c*, the forward first phase is dying away at *a*, and the forward and rising second phase is developing a pole of growing strength at *b*. An examination of the poles produced by these three currents at the same instant show that the reversed third phase, as stated, has developed a strong N pole at *c*, the growing forward second phase is developing a N pole at *b*, and the diminishing forward first phase is permitting its magnetizing effect at *a* to die out. But the dying out at this instant of the forward first phase does not mean the extinction of the S pole at this point, for the reason that the reversed third phase at *c* and the forward second phase at *b* are contributing their effect in producing an S pole near *a*. The system involved therefore, in connection with the rise and fall of the various poles and their strengths in the ring may be summarized with respect to the rotary position of the N and S poles as follows:

Direction and number of phase.	Kind of pole it produces in the ring.	Where pole is produced.
First phase forward.	A south pole.	A *a*.
Second phase forward.	A south pole.	A *b*.
Third phase forward.	A south pole.	A *c*.
First phase reversed.	A north pole.	A *a*.
Second phase reversed.	A north pole.	A *b*.
Third phase reversed.	A north pole.	A *c*.

From this it is evident in this particular field winding that the first, second, and third phase forward produce a S pole wherever they operate; and that the first, second, and third phase reversed produce a N pole wherever they operate, as may be readily ascertained by tracing the windings around the ring where the currents respectively enter and leave. If the windings around the ring were reversed, the poles would also be reversed, and the upper pole at *a* would

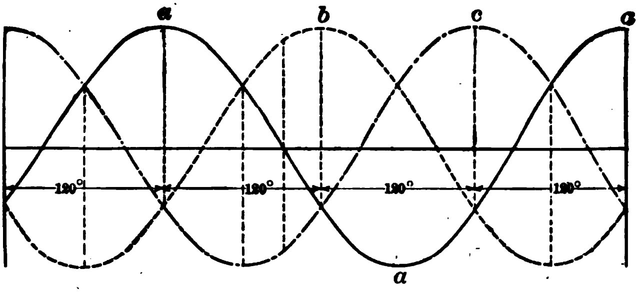


FIG. 117.—Examination of the Three Phases Entering and Leaving the Coils.

be a N instead of a S when the first forward phase entered.

Tracing the Phases in the Circuits.—The point of importance is to trace the currents of the phases as they enter and leave at *a*, *b*, and *c* respectively (Fig. 117), and to see whether they conflict in any way with one another during this rather complex operation. For instance, when the first phase forward enters at *a*, how are the currents of the second and third phases, whether forward or reversed, entering and passing out of the lines and coils? When the first phase forward enters at *a*, the third phase forward is diminishing at *c*, and the second phase reversed is rising to its greatest value in *b*. Therefore a current is entering at *a* (Fig. 118), leaving at *b*, and entering at *c*. To reiterate, this simply means that the current of the first phase forward is entering *a*, the current of the second phase is reversed in *b*, and the current of the third phase forward, though diminishing, is still entering *c*. On this basis there are two entering currents and one leaving current in the coils when the first phase forward enters at *a*. Before the current is quite at its maximum at *a*, however, and in the A and B coils in consequence, the forward third phase has reached zero, passed it, and become reversed. Therefore, when the first phase forward is at its greatest strength, both the second and third phases are reversed. This is generally indicated by the arrows in such circuits pointing in appropriate directions. In the case specified they would point inward at *a*

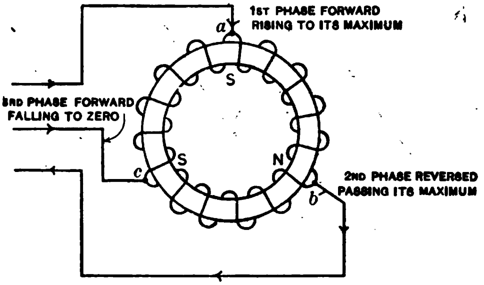


FIG. 118.—Direction of the Phases of Current when the Cycle Begins.

and outward at *b* and *c*. What is true of the flow of current in the coils when the first phase forward enters at *a* is also true in succession at *b* and *c* as the second and third phases forward enter at *b* and *c* respectively in turn and at their proper time. But the current at *c* is still entering when the current at *a* is beginning to enter and that at *b* is flowing in a reversed direction. This calls for an examination of the currents in the three wires at this particular stage of the development of the phases as well.

More Current in One Main than Another.—The three sine waves of the three phases show conclusively that when the current of the first phase forward is entering *a* the current of the second phase reversed is leaving *b* and the current of the third phase forward is still in *c*. The current, therefore, in the upper wire is an entering current whose natural return is out at *b* by way of the conductor connected thereto, until the third phase forward at *c* reverses, which it will speedily do, and then permit the entering forward first phase at *a* to return also by way of *c*. But this will not transpire until the *b* wire has been used as a common return by the first phase forward from *a* and the third phase forward from *c*. The third phase forward from *c* soon dies out, and the current entering at *a* passes out by way of *b* and *c*. Before the reversed second phase at *b* dies out the reversed third phase at *c* begins to augment in strength. This means that both the *b* and *c* wires are carrying current reversed in direction to that of the *a* wire. The current in the *a* wire eventually dies out an instant after the current in the *b* wire has reversed, by which is meant that the forward first phase ceases an instant after the forward second phase begins at *b*. But the first phase now begins as a reversed current, thus providing in the two wires *a* and *c* a return for the current now entering at *b*. The same condition will prevail, as far as this principle is concerned, in connection with the falling away of the forward second phase in *b*. The reversed first phase at *a* will grow in strength, also the reversed third phase at *c*, and they will then decline, the result being that the forward second phase at *b* will fall to zero a little after the reversed third phase reverses and becomes a forward third phase, and the reversed first phase reaches its maximum. This means an entering current at *c*, an outgoing current at *b*, and an outgoing current at *a*. The idea thus presented shows the use of the *c* wire with respect to the other two, not only in this, but in the other cases, where the current distribution is altered with reference to the *b* wire as a return, as well as the *a* wire.

Generating a Three-phase Current. — Using a three-phase current to develop a rotary field is the most significant application now made of a current of this character. By this is meant that the three-phase current implies a three-phase motor primarily, a three-phase wiring system, and the possible application of the power at low pressure in three-phase form to lighting directly. The generation of a so-called three-phase or three-current form of power can be best understood with respect to three armatures of an equal number of conductors and of equal size affected by three fields of an equal number of poles. To generate three currents succeeding one another at an equal interval of time, the armatures evidently could not be identically situated as far as their conductors are concerned. If the conductors of one armature (Fig. 119) had passed the neutral line between any two given poles, it would be necessary for the conductors of the second armature (Fig. 120) to pass the same neutral line of the second field 120 degrees behind. The conductors of the third armature (Fig. 121) would have to be so situated with respect to the neutral line between any two given poles that they in their turn would follow up 120 degrees behind. Thus the three armatures then individually produce three single-phase currents a short interval behind one another, acting indepen-

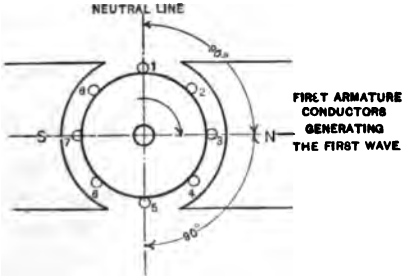
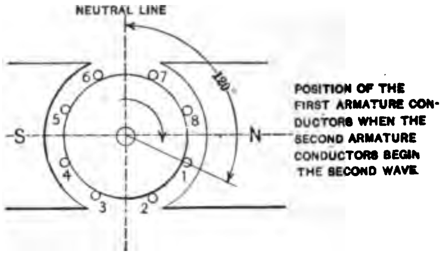


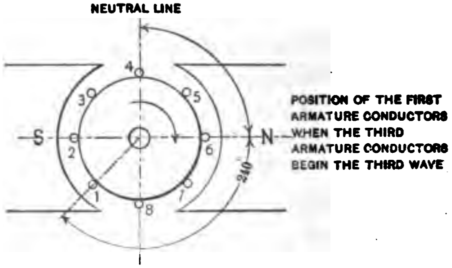
FIG. 119.—Beginning the First Phase.

dently as described. But a combination of this character would simply represent the equivalent of three currents from three separate machines that could be better generated from a single machine provided with an armature winding of adequate design. This, then, leads to a consideration of the manner in which a generator with only one field and one armature can be constructed so as to produce what science and engineering demand, namely, a three-phase current consisting of three electromotive forces and their



POSITION OF THE FIRST ARMATURE CONDUCTORS WHEN THE SECOND ARMATURE CONDUCTORS BEGIN THE SECOND WAVE

FIG. 120.—Beginning the Second Phase.



POSITION OF THE FIRST ARMATURE CONDUCTORS WHEN THE THIRD ARMATURE CONDUCTORS BEGIN THE THIRD WAVE

FIG. 121.—Beginning the Third Phase.

corresponding currents, the three electromotive forces following 120 degrees apart.

The Three-phase Generator.—In a three-phase generator the field may be built up of two, four, six, eight, or ten poles, etc. Each two poles, from the neutral place on each side of them, represent 360 degrees. For instance, if a N and a S pole are considered, the neutral line of the N pole, as shown (Fig. 122), and that between the N and S poles include 180 degrees. The neutral line between the two poles and the neutral line of the south pole also include 180 degrees. In other words, each pole, from its neutral line on each side of it, represents 180 degrees. It is thus evident that conductors can be so situated on a single armature embraced by a field of many poles that their position will enable them to successfully occupy the same places in the field and yet remain an unalterable distance apart.

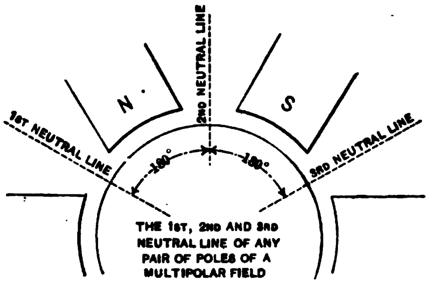

2ND NEUTRAL LINE
N
S
1ST NEUTRAL LINE
3RD NEUTRAL LINE
180°
180°
THE 1ST, 2ND AND 3RD NEUTRAL LINE OF ANY PAIR OF POLES OF A MULTIPOLAR FIELD

FIG. 122.—Angular Distance between Neutral Lines.

The positions such conductors must occupy will on this basis be one-third of the distance between the first neutral line of the N and the last neutral line of the S of any pair of poles. If a series of conductors belonging to the winding producing the first

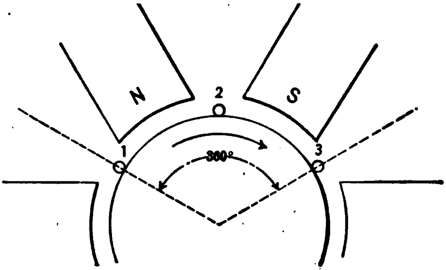


FIG. 123.—First-phase Conductors 360 Degrees Apart.

phase are numbered 1, 2, 3, etc., then, as the rotation proceeds, these conductors change their positions, leaving the neutral space and moving through the space (Fig. 123) indicated as equal to 360 degrees. Each conductor successively develops first a forward phase and then a reverse phase, depending upon whether it passes under a N or S pole. For instance, conductor 1 enters under the N pole, passes the neutral line, and enters under the S pole to the neutral line beyond it. During this change of position it generates a forward current under the N pole and a reverse current under the S pole. Each of the conductors of this first-phase winding are connected up in such a manner that their electromotive forces are in series. Their position under the poles causes them to develop waves that flow in the same direction. This may be readily understood by noting that the conductors are connected at their ends, as shown (Fig. 124), so as to throw the currents in series with one another. The further expansion of this principle would permit of a coil under one pole being connected to an oppositely wound coil under an adjacent pole, instead of only one conductor. By this means a greater E.M.F. can be generated in any given winding. The set of conductors referred to, however, are those employed in this system of three-phase generation, transmission, and distribution to develop only one phase, irrespective of the action of other conductors on the same armature.

The Three Armature Windings.—The three windings on a three-phase armature are therefore so placed that if the first is situated, as stated, at the neutral line, then the second is placed one-third of the distance behind it, and the third winding one-third of the distance behind the second. In other

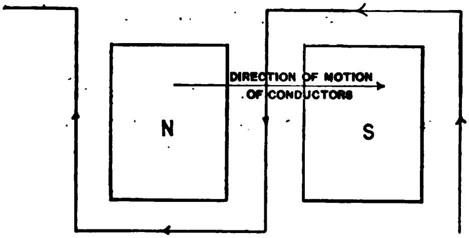


FIG. 124.—Conductor Connected to Show Flow of Current in One-phase Winding.

words, the distance referred to is the distance representing the 360 degrees between two poles. On this basis, 120 degrees is one-third of this distance, or the degree of separation between the first, second,

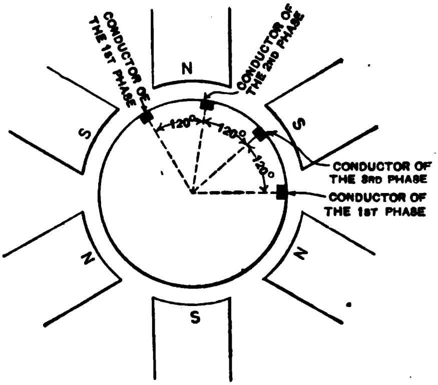

CONDUCTOR OF THE 1ST PHASE
N
CONDUCTOR OF THE 2ND PHASE
S
S
120°
120°
120°
CONDUCTOR OF THE 3RD PHASE
CONDUCTOR OF THE 1ST PHASE
N
N
S

FIG. 125.—Conductors 120 Degrees Apart on Armature.

and third set of conductors on the armature. In the illustration (Fig. 125) four conductors are shown in their respective positions on the armature. They are situated 120 degrees apart, thus giving four conductors: one at the beginning of the first phase, one at the beginning of the second phase, one at the beginning of the third phase, and one at the end of the 360 degrees, marking the beginning of the first phase again, etc. The arrangement is therefore as follows:

First—A set of conductors situated in such positions that all around the armature (Fig. 126) they may be found at the neutral lines. These conductors will be able to produce the first phase (Fig. 127) if connected to two collector rings.

Second—A second set of conductors situated in such a position that all around the armature they may be found 120 degrees away from the conductors situated at the neutral line. This second set of conductors will be able to produce the second phase if connected to two collector rings.

Third—A third set of conductors situated in such a position that all around the armature they may be found 120 degrees away from the second set of conductors. This third set of conductors will be able to produce the third phase if connected to two collector rings.

According to these conditions, the entire winding will result in six collector rings, each pair permitting a single-phase current to issue and reverse, and each phase 120 degrees away from its neighbor. If the case is presented of one set of conductors situated

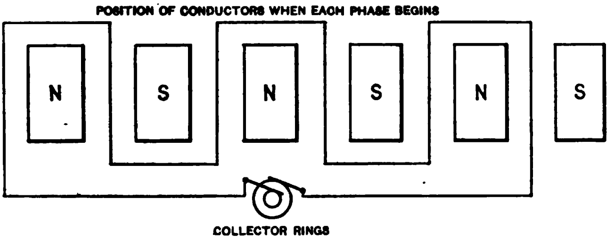


FIG 126.—Development of Winding with Conductors at the Neutral Line.

at the neutral line, and the magnets and conductors are shown in a development (that is, laid out flat), then it will be evident how the first set of conductors

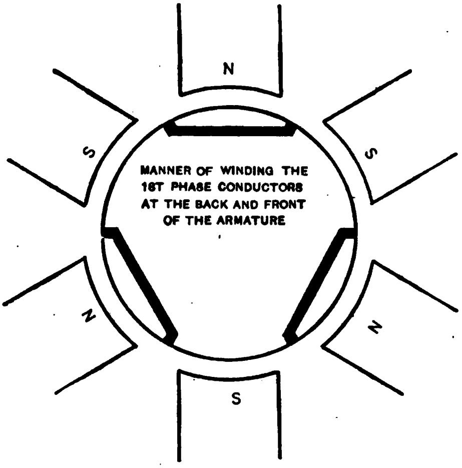


FIG. 127.—Conductors of One of the Phases. E.M.F. about to Begin.

are wound in armature slots and connected to two collector rings. The conductors represent what is called wave winding—a back-and-forth winding with conductors passing under N and S poles, and so connected that its individual elements are in series.

A Six-wire Three-phase System.—By using a pair of collector rings for each phase, there will necessarily be six wires in use, two to each collector. In this case the windings are distinct from one another, as shown in the illustration (Fig. 128), in which the development of the poles and conductors makes evident the relationship one set of conductors bear to another. The fact that this system of connections calls for six wires makes it only the equivalent of three single-phase systems associated together, without any advantage in the amount of copper used. The production of a three-phase current, however, whose phases are 120 degrees apart, means a rotary field and a self-starting motor. The reduction of the number of conductors was imperative, if possible, for the reason that in this manner the amount of copper necessary became less than that of merely three single-phase generators, thereby giving the

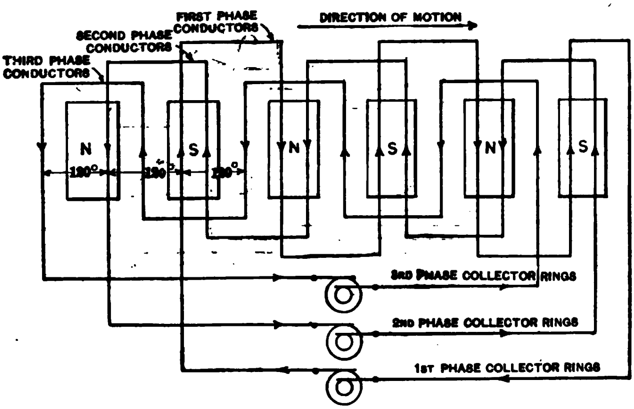


FIG. 128.—Six Rings and Six Mains for a Three-phase System.

double advantage found in not only the rotary field, but the economic gain in copper when power is transmitted.

A Four-wire Three-phase System.—By means of a certain method of connecting up the three sets of armature conductors, it is possible to use only four instead of six wires (Fig. 129), and yet preserve at the same time the individuality of the three phases as though they were generated separately. The generator in this case employs four collector rings for the following reason: The three windings are connected together at a common junction and their three free ends connected respectively to three single col-

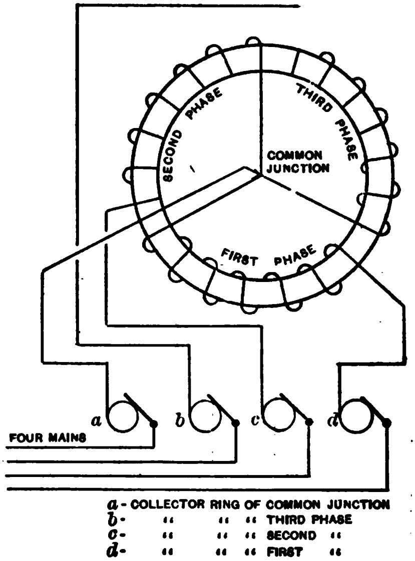


FIG. 129.—The Y System of Connecting Up a Three-phase Armature Winding for Four Mains.

lector rings. The common junction of the three windings is also connected to one ring. There are therefore four main wires carrying the three phases, one of which, however, acts entirely in the capacity of a common return. The Y system of connecting up the armature serves as a basis for this idea. Each of the arms of the Y terminates in a single collector ring, and the common junction of all three in another ring, making four in all. Four mains connect to the brushes pressing on these rings and act as the source of supply outside. If the three phases supply current to circuits which are electrically equal, then the three wires connecting to their particular armature coils will carry all the energy. But if the reactance and resistance they meet with are not equal, the fourth wire becomes necessary to carry the difference thus developed. This is readily understood by considering .three separate single-phase generators and their outside circuits. If in this case their reactances and resistances are not equal, their currents will not be equal. One may carry twice as much as the other in consequence. For this reason, when the three phases are produced from a common armature, and in doing their work meet with the unequal electrical conditions mentioned, provision must be made to take up the difference, if any, between them. If no difference does exist, the fourth conductor connecting to their common junction becomes unnecessary, and the machine will run well with only three rings.

Two Phase with Three Mains.—A two-phase system also presents a case in which the four wires may be cut down to three; as in a three-phase system, six wires may be cut down to four or even three. In a two-phase system, however, this method of connecting up simply means the use of three collector rings instead of four, by merely joining together two of the ends of two coils or systems of coils, each of which produces one phase. By this is meant that in the case of two coils, each of which produces one phase, there are four ends. If one end from each coil is run out to a separate collector ring, there is left one end from each coil, or two ends altogether, which may

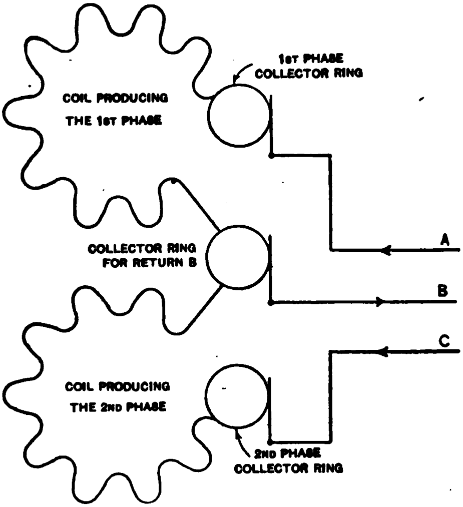

1ST PHASE COLLECTOR RING
COIL PRODUCING THE 1ST PHASE
COLLECTOR RING FOR RETURN B
A
B
C
COIL PRODUCING THE 2ND PHASE
2ND PHASE COLLECTOR RING

FIG. 130.—General Principle of a Three-wire Three-phase System of Winding.

be joined and run out to a third ring, as shown in the illustration (Fig. 130). The common connection for the two armature windings, which in this case are represented as two wave windings so placed on the armature that the proper phase difference of 90 degrees results, acts as a single wire performing the function of two, according to the particular phase and its direction when operating. For instance, according to the principle involved in the co-operation of two single-phase currents one 90 degrees behind the other, the current in the first phase is at zero and about to reverse, when the current in the second phase is at its maximum. Therefore, the forward second phase falling to zero must return by way of C from B, and the reversed first phase must pass out at B, returning by way of A. The arrows show the directions of the currents when the forward second phase is subsiding and the reversed first phase is rising to its maximum power.

CHAPTER XII

CLASSIFICATION OF ALTERNATOR ARMATURE WINDINGS. —ARMATURE SLOTS PER PHASE. — THREE-PHASE ARMATURE COILS EQUALLY LOADED.—AMOUNT OF CURRENT AND PRESSURE IN EACH PHASE IN THE RECEIVING CIRCUITS.—AMPERES AND VOLTS IN A THREE-PHASE Y-CONNECTED RECEIVING CIRCUIT.—AMPERES AND VOLTS IN A THREE-PHASE DELTA-CONNECTED RECEIVING CIRCUIT.—DIFFERENCE IN POWER RECEIVED BY DELTA AND Y CIRCUITS.—POWER IN THE MAINS OF A THREE-PHASE SYSTEM. —POWER THE SAME FROM A DELTA- OR Y-WOUND ARMATURE.—THREE-PHASE Y SYSTEM FOR POWER TRANSMISSION.—PRACTICAL COMPARISON OF THE Y AND DELTA SYSTEMS.—CURRENTS IN THE TWO SETS OF CONDUCTORS.—REVIEW OF THE FACTS.—STAR AND MESH TWO PHASE. — THE STAR-CONNECTED FOUR-PHASE SYSTEM.

Classification of Alternator Armature Windings. —In direct-current armature windings there are found two general classifications, called lap and wave windings. The alternator armature winding, which may be considered as belonging to the latter type, presents a still further classification, more with reference to the poles, however, than the style of winding. In other words, there may be but one coil per pole, or there may be two or more coils per pole. If there is but one coil per pole, it simply means that a single phase or a two- or three-phase current is being produced, as the case may be, by one set of coils for the one phase, or two or three sets of coils for the two- or three-phase current, but only one coil per pole per phase. If there is more than one coil per pole per phase, then a single phase, or any phase of more than one of two or three phases, is being produced by more than a single coil per pole. For such reasons as these it is necessary to make a distinction between *single-coil windings* and *multi-coil windings*, otherwise called *concentrated* in the first case and *distributed* winding in the second case. Both cases may be said to refer largely to the number of slots in the armature used under each pole for each phase.

Armature Slots per Phase.—There may be only one slot allowed under each pole at a time, though it may contain one or more conductors. In a single-phase armature the current flows forward in the conductor under one pole, and reversely in the conductor under the next pole. A coil winding, therefore, contained in two slots which are under opposite poles will develop a distinct rise and fall of E.M.F. If there is more than one slot to each pole for the generation of a single-phase current, the winding becomes multi-coil in character. It is therefore a simple matter to understand how a two-phase current may be produced, either by means of two windings found in two sets of slots, but only one slot to each phase, or by means of two windings, as before, but with each phase produced by means of conductors which occupy more than one slot per pole per phase. The type of winding thus depends, for its name at least, upon the number of slots utilized, as described, under one pole for one phase.

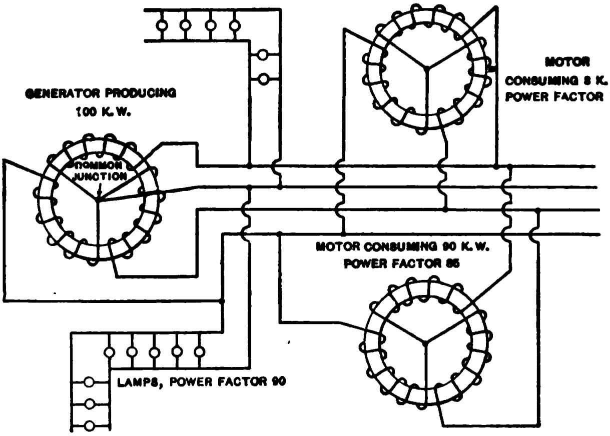


FIG. 131.—Generators, Motors, and Lights, with a Fourth Wire from the Common Junction to Sustain a Balance. The Usual Method in Practice with a Y Wound Generator Armature.

Three-phase Armature Coils Equally Loaded.—The necessity for keeping the three lines equally balanced is a requisite of a three-phase system (Figs. 131 and 132) in which the fourth wire is dispensed with. The three great divisions of the armature coils will not otherwise produce equal currents. The distribution of the load, therefore, must be such that this condition is preserved. When synchronous or induction motors are connected up, or any other class of current-consuming devices, such as rotary converters for instance, the balance in this respect must be retained. As a general rule, the fact that such apparatus will naturally take current equally from the three mains is sufficient reason for a belief in the tri-equal character of the distribution. Both delta and Y systems of armature winding will supply but three mains for transmission and distribution under such circumstances, though it can be readily understood that current from a delta armature winding may be utilized in a Y winding of a motor or converter. The reverse is also true, that current from a three-main Y armature winding may be used for the rotation of a delta-wound motor, etc.

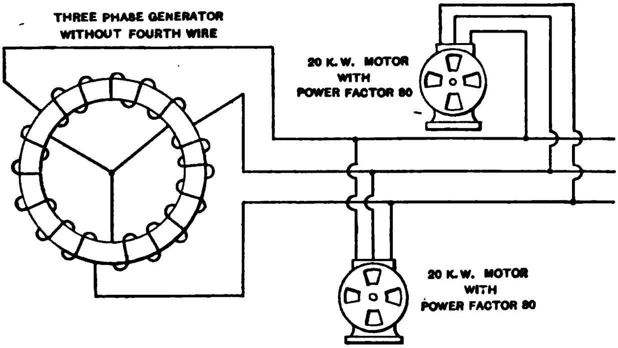


FIG. 132.—Where the Fourth Wire from the Common Junction is not Necessary because the Wires are all Equally Loaded.

Amount of Current and Pressure in Each Phase in the Receiving Circuits.—The amount of current in amperes, and the degree of potential in volts in the mains of a three-phase system when connected up according to the delta and Y scheme and balanced, must be considered in order to present a definite view of the amount of power each will supply respectively in each phase in the receiving circuits. There is a distinction to be made, however, between the mains and the terminals of a given receiving circuit in three-phase practice. For instance, as stated, the three mains may emanate from either a delta or a Y system of armature connections. In this case, also as stated, they may be connected up to either delta or Y receiving circuits, such as motor terminals, etc. Suppose the three-phase current is received in a Y-connected piece of apparatus (Fig. 133), then the questions arising are as follows: How many amperes will be found in each phase or branch of the receiving circuit? Also, how many volts will be found between the terminals of the receiving circuit? The answers will be to the effect, that in this design of receiving circuit (the Y type) the current in each section or phase will be equal to that found

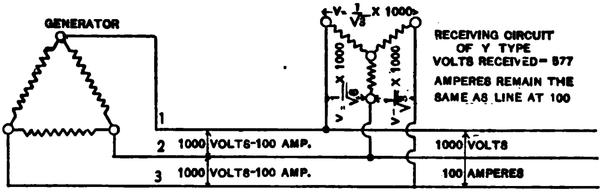

GENERATOR
$V = \frac{1}{\sqrt{3}} \times 1000$
$V = \frac{1}{\sqrt{3}} \times 1000$
$V = \frac{1}{\sqrt{3}} \times 1000$
RECEIVING CIRCUIT OF Y TYPE
VOLTS RECEIVED = 577
AMPERES REMAIN THE SAME AS LINE AT 100
1
2
3
1000 VOLTS-100 AMP.
1000 VOLTS-100 AMP.
1000 VOLTS
100 AMPERES

FIG. 133.—Power Received by a Y Circuit through Each Phase.

in the main supplying it with current. On the other hand, the difference of potential in volts found between the terminals of the receiving circuit or in each phase will be equal to a certain constant times the difference of potential between any two of the main wires. Representing this idea in a more definite form, it may be said that the volts between any two terminals of the receiving circuit or in any phase will be equal to $\frac{1}{\sqrt{3}} \times E$, where E is equal to the volts measured between any two main wires. But the value of $\sqrt{3} = 1.732$, and the value of $1 \div \sqrt{3}$ is $1 \div 1.732$ or .577. Therefore $\frac{1}{\sqrt{3}} \times E = .577 \times E$; or, to crystallize this proposition, if a case be considered in which the pressure between any two mains is 1,000 volts, the system being three phase, the question to decide is the voltage at the receiving points. This is evidently equal to .577 × 1,000, or 577 volts, while the amperes are simply those of the two mains.

Amperes and Volts in a Three-phase Y-connected Receiving Circuit.—To recapitulate, it may be definitely stated that the current in any section or phase of a Y-connected receiving circuit, and the E.M.F. between any two terminals, are equal respectively to: First, the entering amperes in any two of the mains thus supplying current to a part of the Y circuit; and, second, a number of volts equal to .577× the E.M.F. between the said mains, or $\frac{1}{\sqrt{3}} \times E$, where

E equals the potential difference in volts between the said mains. This disposes of the question of the number of amperes and the number of volts obtainable in any phase of this particular form of receiving circuit. If, instead of a Y form consuming the electrical energy, a delta form is employed (Fig. 134),

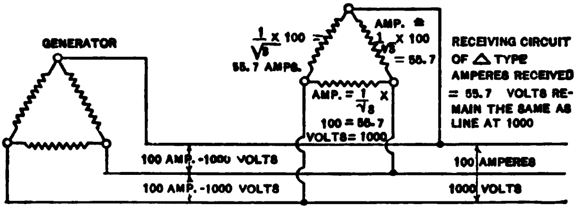

GENERATOR
$\frac{1}{\sqrt{3}}$ x 100 = 55.7 AMPS.
AMP. = $\frac{1}{\sqrt{3}}$ x 100 = 55.7
AMP. = $\frac{1}{\sqrt{3}}$ x 100 = 55.7
VOLTS = 1000
RECEIVING CIRCUIT OF △ TYPE AMPERES RECEIVED = 55.7 VOLTS REMAIN THE SAME AS LINE AT 1000
100 AMP. -1000 VOLTS
100 AMP. -1000 VOLTS
100 AMPERES
1000 VOLTS

FIG. 134.—Power Received by a Delta Circuit through Each Phase.

then the calculation of the volts and amperes is conducted on slightly different lines.

Amperes and Volts in a Three-phase Delta-connected Receiving Circuit.—Under the same circumstances as already noted, power in the form of a three-phase current may be sent into a receiving circuit whose system of winding is of the delta instead of the Y type. In this case the question also arises as to what is the current in amperes and the E.M.F. in volts in any phase and between any two terminals of the receiving circuit. The answer to this question will be found in the statement that the E.M.F. in any phase and between any two points of the receiving circuit will be equal to the E.M.F. of any two of the mains. On the other hand, the current in amperes in any phase of the receiving circuit will be equal to the current in any one main multiplied by .577. In other words, to find the amperes in any phase of any branch of a receiving circuit of the delta type, the formula applying is, current in amperes = $\frac{1}{\sqrt{3}} \times$ current in any main. To take a specific case as an example: Suppose a three-phase system operates a motor whose circuits are delta-connected, and the pressure between any two mains is equal to 1,000 volts; then what is the current in amperes received in each phase of the motor if the current in each main equals 100 amperes? According to the method given, the E.M.F. between any two of the terminals of the receiving circuit is equal to the E.M.F. between any two of the power mains delivering the pressure. But the current in any branch or phase of the motor circuit is equal to $C \times \frac{1}{\sqrt{3}}$, where C equals the current in the main wire. Then the current in that particular phase is equal to $.577 \times C$, or $.577 \times 100 = 57.7$ amperes.

Difference in Power Received by Delta and Y Circuits.—The difference in power received by delta and Y circuits may be readily noted in the method of obtaining the value of the volts and amperes in any phase of a three-phase circuit consuming the power (Fig. 135), and connected up according to either a delta or a Y system. This difference is found in the calculation of volts and amperes as follows, where E equals volts and C equals amperes of the three-phase mains:

First—Volts in any phase of a Y-connected three-phase circuit $= .577 \times E$.

Second—Amperes in any phase of a delta-connected three-phase circuit $= .577 \times C$.

In other words, where the power-consuming circuit is of delta type the volts remain the same as in the mains, but the amperes are multiplied by a constant .577. Where the power-consuming circuit, however, is of the Y type, the amperes remain the same as in the mains, but the volts are multiplied by a constant .577. These figures relate particularly to motors of

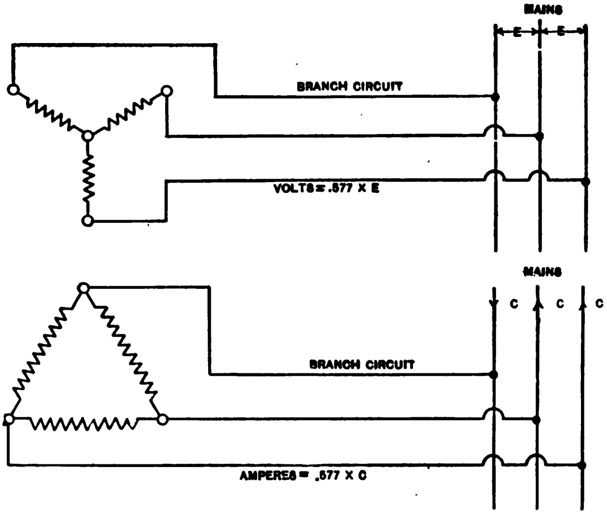


FIG. 135.—Difference between the Volts and Amperes of Y and Delta Receiving Circuits.

the three-phase type; such motors may be self-starting or not. In other words, it may not be desirable to take advantage, in certain cases as found in practice, of the fact that a three-phase current will make them self-starting. In consequence, three-phase motors may be synchronous or non-synchronous. They may have to be started from rest by external means, or they may start themselves. Whichever is the case, it is of equal interest to know what the power generated by the alternator represents as well as that of the motor or transformer generally receiving and consuming it.

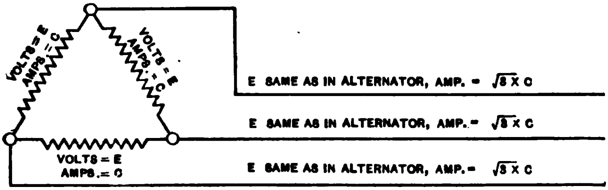

VOLTS = E
AMPS = C
VOLTS = E
AMPS = C
VOLTS = E
AMPS. = C
E SAME AS IN ALTERNATOR, AMP. = √3 x C
E SAME AS IN ALTERNATOR, AMP. = √3 x C
E SAME AS IN ALTERNATOR, AMP. = √3 x C

FIG. 136.—Current and Pressure in Delta Armature and its Mains.

Power in the Mains of a Three-phase System.—The power sent into the mains of a three-phase system by the alternator, whose armature may be delta or Y wound, must be estimated in order to complete the method of calculating three-phase power. If the E.M.F. of each phase be called E, and the current of each phase C of the generating coils, then, as there are three such coils or windings, the power sent into the mains will be equal to the following: The E.M.F. of the mains obtained from a delta-wound armature will be equal to the E.M.F. of the first, second, or third phase (Fig. 136) of the three sets of coils. In this respect, therefore, to make the matter clear, a delta-wound three-phase armature only supplies the mains with the same pressure as they are rated at. On the other hand, the exact current C of each of the three sets of coils does not appear in the line wires. The current which actually appears is $\sqrt{3} \times C$, or $1.732 \times C$, whatever C may be. This being the case, the current C and the electromotive force E, which a delta-wound alternator armature sends into the power wires, will, when multiplied together, give a product equal to $\sqrt{3} \times E \times C = 1.732 \times E \times C$.

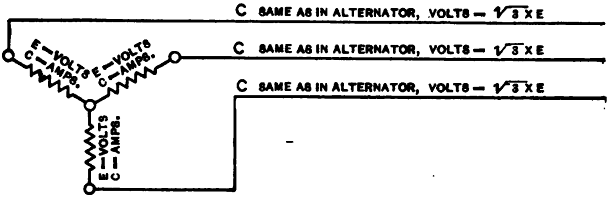

C SAME AS IN ALTERNATOR, VOLTS — $\sqrt{3} \times E$
C SAME AS IN ALTERNATOR, VOLTS — $\sqrt{3} \times E$
C SAME AS IN ALTERNATOR, VOLTS — $\sqrt{3} \times E$
E — VOLTS
C — AMPS.
E — VOLTS
C — AMPS.
E — VOLTS
C — AMPS.

FIG. 137.—Current and Pressure in Y Armature and its Mains.

An examination of the value of the current in amperes and the electromotive force in volts obtained in the line or power wires from a Y-connected alternator armature (Fig. 137) shows the following: The current which represents the full load rating of each of the coils, if called C, is exactly the current which will be found in each of the mains when the armature is developing its maximum current. In other words, an armature of this type sends into each of the three wires the full current of each of its three phases. The electromotive force, however, is different, in that the volts found in each of the power lines in pairs will be $\sqrt{3} \times E$, where E equals the volts at which each phase of each of the three windings is rated. The value, therefore, of the product of the two elements of power is equal to $\sqrt{3} \times E \times C$, or, as $\sqrt{3} = 1.732$, the value of $\sqrt{3} \times E \times C$, as in the former case, equals $1.732 \times E \times C$.

Power the Same from a Delta- or Y-wound Armature.—The following figures illustrate the identity in values of the power obtained from an armature of given size, whether it is connected up according to the delta or the Y system. For instance, if a delta-wound armature produces a rated electromotive force of 1,000 volts and a rated current of 100 amperes, and a Y-wound armature of equal size produces a rated electromotive force of 1,000 volts and a rated current of 100 amperes, what are their respective power ratings? According to the method indicated, the ratings would be as follows, as far as the line output is concerned:

First—For the delta-wound armature the volts = 1,000, and the amperes = $1.732 \times 100 = 173.2$.

Second—For the Y-wound armature the volts = $1.732 \times 1{,}000 = 1{,}732$, and the amperes = 100.

This result emphasizes the necessity of knowing and recognizing the differences in volts and amperes produced by armatures of alternators so wound, and the character of the receiving circuits. The power produced by a three-phase generator is therefore equal to the product of 1.732 times the volts between two mains times the amperes in one main. For instance, if the volts from a three-phase generator entering the line equal 10,000, and the amperes equal 100, the power on tap (without considering the different power factors of the various circuits to which it would be supplied) will be equal to 1.732 × 10,000 × 100, or a total of 1,732,000 watts, or 1,732 kilowatts. From this it is evident that alternators with either form of armature winding (Fig. 138) will be able to send exactly the *same* amount of *power* into the lines. The difference, while not existing as far as the total power is con-

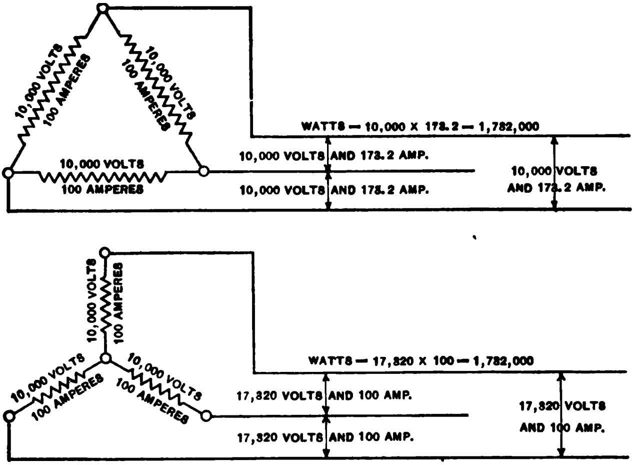

10,000 VOLTS
100 AMPERES
10,000 VOLTS
100 AMPERES
10,000 VOLTS
100 AMPERES
WATTS — 10,000 X 173.2 — 1,732,000
10,000 VOLTS AND 173.2 AMP.
10,000 VOLTS AND 173.2 AMP.
10,000 VOLTS AND 173.2 AMP.
10,000 VOLTS
100 AMPERES
10,000 VOLTS
100 AMPERES
10,000 VOLTS
100 AMPERES
WATTS — 17,320 X 100 — 1,732,000
17,320 VOLTS AND 100 AMP.
17,320 VOLTS AND 100 AMP.
17,320 VOLTS AND 100 AMP.

FIG. 138.—Power Received is the Same from Both Armatures, when Delta or Y Wound.

cerned, will be found mainly in the number of amperes and volts in the lines. For instance, in the cases cited, the volts in one system will be 1,000 and the amperes 173.2; in the other system the volts will be 1,732 and the amperes only 100. It is quite evident from this that for greater economy it would seem right to use the higher pressure, or the Y-wound armature. But unless assurance can be had of an equal load on each line, a fourth wire would be necessary from the common junction. With this settled, however, the higher-pressure system would be the best for this and other reasons.

Three-phase Y System for Power Transmission.—Not only is the Y system of connections deemed preferable, because, as shown in the case of transmitting power, a Y-connected armature sends 1,732 volts into the line, whereas a delta-connected armature sends only 1,000 volts, when each armature winding generates 1,000 volts—not only for this reason, as stated, is the Y-connected system more in vogue than the delta connected, but because even a casual investigation of the delta or mesh connection clearly shows the risk run through the possibility of other than the fundamental electromotive forces acting on the mesh to produce a circulation of parasitical currents (Fig. 139). By this is simply meant the following: That a fundamental wave of electromotive force is the wave of E.M.F. generated by the same armature conductors successively passing a N pole and a S pole. There is therefore produced a distinct back-and-forth flow of current of a rising and falling pressure and amperage. But certain conditions may be effective in producing a series of electromotive forces, which act in the capacity of secondary waves, of either a lower or higher E.M.F., but of a higher frequency than the so-called fundamental wave. These may be and frequently do become the cause of currents around the mesh that represent a waste of energy. For these two reasons, therefore, the mesh or delta system of connections in power transmission and distribution is giving way to the more general use of the Y or star system of connections as it is sometimes called, except when rotary converters are employed.

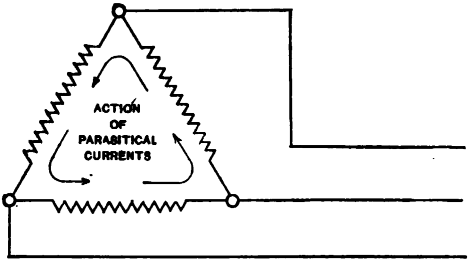


FIG. 139.—Flow of Electricity Around Mesh Due to Parasitical Currents.

Practical Comparison of the Y and Delta Systems.—Though a comparison of the Y and delta systems of connections might be readily regarded as sufficiently complete by merely contrasting one with the other as a mere scientific proposition, still the comparison is not actually complete in a thoroughly practical sense unless the contrast occurs while power and pressure of a large value are concerned. Power transmission is now on the very threshold of tremendous expansion in the various countries of Europe and America. Where it was originally sent over a distance of only a few miles at a few thousand volts, electrical engineering principles have so developed its possibilities that now the project of transmitting Niagara power to New York City at a pressure of tens of thousands of volts by the three-phase system is no longer a suggestion but an actuality. The steel poles, at this writing, are being erected, and huge triple-petticoat insulators, three to each pole, will suspend, insulate, and support the conductors high in the air.

A case, therefore, which presents the difference between the delta- and Y-connected armatures in service might be best offered in that of a 100-mile power line. A pressure of 60,000 volts would be reasonable in such an instance; and if the power relations are preserved which demonstrate the difference between the delta and Y connections in the generating element, then a 100-ampere current in the three phases—that is to say, 100 amperes in each of the three windings of the two three-phase armatures—would result in the following comparative sets of figures as calculated:

First—Power in the delta-connected system would equal $\sqrt{3} \times 60{,}000 \times 100$, or $1.732 \times 60{,}000 \times 100$, or a product of $173.2 \times 60{,}000$, equal to the total of 10,392,000 watts. But the amperes in the case of a delta-connected armature are equal to $\sqrt{3} \times$ C, or $1.732 \times 100 = 173.2$, and the pressure, according to the facts presented, remains unchanged at 60,000 volts. Thus the line wires would have to be sufficiently large to efficiently carry the total energy at an amperage of 173.2 and a voltage of 60,000. By the expression " efficiently carry " is meant no great loss of power in the wires through drop of potential, or its natural concomitant—degraded electrical energy in the form of heat in the lines.

Second—Power in the Y-connected system would equal $\sqrt{3} \times 60{,}000 \times 100$, as in the previous case; but the energy elements, namely, the operating volts and amperes, would be equal respectively to the following: The potential would not remain the same as in the armature, but would increase to the extent of $\sqrt{3} \times 60{,}000$, which would be equal to $1.732 \times 60{,}000$, or 103,920 volts. The volts as thus presented would reach to a high figure, whereas the amperes remain the same at 100. The total power rating with a non-inductive load is therefore equal to $103{,}920 \times 100 = 10{,}392{,}000$ watts, as in the previous case. The difference in the insulation required with a 60,000-volt and a 103,920-volt current passing through the three lines would be sufficiently great to make it necessary to make provision in the insulators for the increase. The difference also between two systems of power transmission carrying equal quantities of power, generated from armatures of the delta and Y systems of connections respectively, would be the means of calling for extra provision in the way of carrying capacity in the metallic cross-sections of the two sets of conductors to transmit 100 and 173.2 amperes as required.

Currents in the Two Sets of Conductors.—If the carrying capacity of ordinary direct-current wires is considered on a purely ohmic basis, then it is evident that the cross-sections of copper for the three conductors of the Y- and delta-connected armatures respectively would have to be of sufficient circular mils to cause a no greater percentage of lost pressure in one set than the other. The conductors carrying 100 amperes would naturally be smaller than those carrying 173.2 amperes. It is also evident that the conductors carrying the 100 amperes in each phase do so at a pressure of 1.732 times the pressure of the other conductors. In other words, the pressure is higher in one set of conductors than the other, and the amperes are less. It seems, from these facts, that it would be cheaper to build a three-phase power line on the Y system (Fig. 140) than the delta system, as far as the alternator armatures are concerned.

Review of the Facts.—Conclusions to be drawn from this review of the facts are therefore of such a character that it cannot but be obvious that, in the transmission of power at least, the least expense in conductors is found in the case where the line pressure is highest and the amperage lowest. The choice is thus presented in any proposed three-wire three-phase power transmission system of selecting generators with a view of gaining the advantages derived, and not of making a blind choice. The fact that both generators of equal capacity produce equal quantities of power as rated, though both the line voltages and line amperages are different, is sufficient reason for realizing that the difference exists entirely in the form of the output of power. Certain facts must be emphasized in the consideration of transmission problems; and the one that appeals most strongly from an economic standpoint is always that which relates most directly to the size and weight of the conductors composing the transmission lines. This is part of the ultimate financial

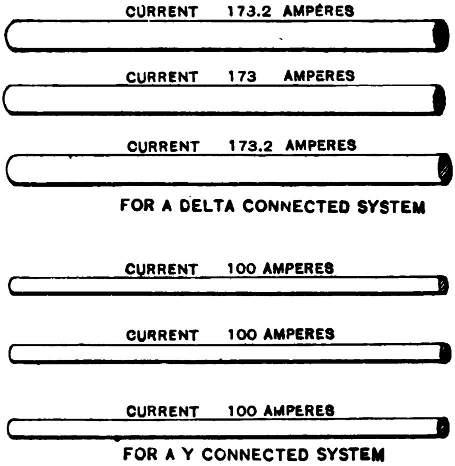


FIG. 140.—Comparison of Copper or Conductor Cross-sections, with Delta- and Y-connected Armatures.

problem, and is fully as important as the purely technical one, if not more so.

Star and Mesh Two Phase.—The greater use to which three phase is now put for transmission purposes leads to its consideration in the first place, as far as the current and pressure in its lines are concerned. But two-phase currents are employed also for power transmission, though they are sometimes regarded as four- instead of two-phase currents. This occurs when the two sets of armature coils are connected in such a manner that they represent four instead of two distinct windings, simply by connecting them together at a common junction. There is thus a form of double two-phase winding developed (Fig. 141), which is called the four-phase star-connected system. On the other hand, the armature windings may be so connected up that, instead of forming four sets of coils, so to speak, wound at right angles to one another, as in the illustration,

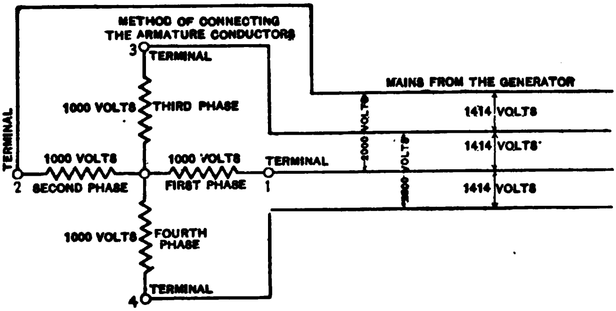


Fig. 141.—A Star-connected Four-phase System.

and meeting at a common junction, they may be wound in a rectangular manner (Fig. 142), forming a sort of square or mesh, thus giving it the name of the mesh-connected four-phase system, as illustrated in the sketch.

The Star-connected Four-phase System.—In this system the four sets of armature conductors are connected, as described, to a common junction, and develop really two phases, though sometimes called four, as illustrated. The four phases, however, are really two outward and two inward pulses of E.M.F. on the same basis that a single-phase current might be considered as consisting of two phases, one forward and one backward, after a certain interval has passed. But irrespective of this theoretical consideration, the E.M.F. between any two terminals representing the ends of two consecutive sets of coils is equal to twice the E.M.F. of any one of the coils. For instance, the E.M.F. between the terminals 3 and 4 will be 2,000 volts if the E.M.F. of either one

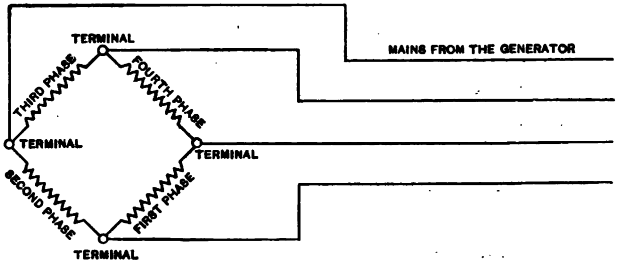


FIG. 142.—A Mesh-connected Four-phase System.

is 1,000 volts. But the E.M.F. between the terminals 1 and 3 will not be 2,000 volts. It will be equal to $\sqrt{2} \times 1{,}000$, or $1.414 \times 1{,}000 = 1{,}414$ volts. Thus, in a system of cross or star connections as given, the electromotive force between any two sets of coils representing opposite rays of the star will equal twice that of one. But the electromotive force of any two terminals representing adjacent rays of the star is equal to 1.414 times the E.M.F. of one.

CHAPTER XIII

VOLTAGES EXISTING IN A STAR-CONNECTED TWO-PHASE SYSTEM.—VOLTAGES EXISTING IN A MESH CONNECTED ACCORDING TO THE TWO-PHASE SYSTEM.—AMPERAGES IN A STAR- AND MESH-CONNECTED TWO- OR FOUR-PHASE SYSTEM.—COMPARISON OF THE COPPER REQUIRED FOR DIFFERENT SYSTEMS.—TWO-PHASE FOUR-WIRE SYSTEM WITH TRANSFORMERS.—TWO PHASE FOUR WIRE TO TWO PHASE THREE WIRE.—THREE-PHASE THREE-WIRE DELTA.—THREE PHASE THREE WIRE Y OR STAR CONNECTED.—COMBINATION Y AND DELTA.—CHANGING TWO PHASE INTO THREE PHASE.—A COMPLETE PHASE- AND PRESSURE-TRANSFORMING SYSTEM.—CHANGING TWO PHASE INTO THREE PHASE AND BACK INTO TWO PHASE.—FEATURES OF TRANSFORMER DESIGN.—CAUSES OPERATING TO PREVENT THE DEVELOPMENT OF A CONSTANT POTENTIAL AT THE TERMINALS OF THE SECONDARY.

Voltages Existing in a Star-connected Two-phase System.—The general conclusions to be drawn from an examination of the conditions existing in a star-connected two- or four-phase system may be summarized for reference in the following manner:

First—Conductors connected to those coils representing the first and second phase have a pressure of 2 × E, if E equals the electromotive force of one coil, or $2 \times 1{,}000 = 2{,}000$ volts between them.

Second—Conductors connected to terminals representing what may be called consecutive phases, such as the second and third, have a pressure of $\sqrt{2}$ or $1.414 \times E$, if, as stated, E equals the electromotive force of one coil, or $1.414 \times 1{,}000 = 1{,}414$ volts between them.

Third—Conductors connected to coils generating what may be called the third and fourth phases have a pressure equal to 2 × E, if E equals the electromotive force of one coil, or $2 \times 1{,}000 = 2{,}000$ volts between them.

Fourth—Conductors connected to the terminals of two adjacent coils, such as those issuing from the first and fourth phases, have a pressure equal to $\sqrt{2} \times E$, if E equals the electromotive force of one coil, or $1.414 \times 1{,}000 = 1{,}414$ volts between them. According to this data, the conductors next to each other have a pressure of 1,414 volts between them. That is to say, there are 1,414 volts between the conductors connected to the first and fourth, the first and third, and the third and second phases. But between the conductors connected to the first and second and the third and fourth phases the pressure is that of two successive phases in series, or a total of 2,000 volts. This *résumé* of the relationship between phase and phase, both with respect to its bearing upon one 90 degrees away, as well as one which may be regarded as constituting part of another, will prove valuable in attaining a full realization of the successive actions transpiring with the coils of a star-connected two-phase armature.

Voltages Existing in a Mesh Connected According to the Two-phase System.—When a mesh system is employed to carry a two- or four-phase current, the lines run from four points in the armature winding (Fig. 143), situated respectively at equal distances apart. As stated, currents produced from this type of connections may be efficiently employed to operate rotary converters, whose armatures would also belong to the same type of windings. The value of the currents and electromotive forces produced in this manner can be summed up in the following statement: If the potential developed by each phase be consecutively termed that of the first, second, third, and fourth phase, then, calling E the E.M.F. of each of these phases, the value in volts between any two coils to which taps are made will be $\sqrt{2} \times E$. The illustration, in this respect, shows the exact voltage resulting from this condition of

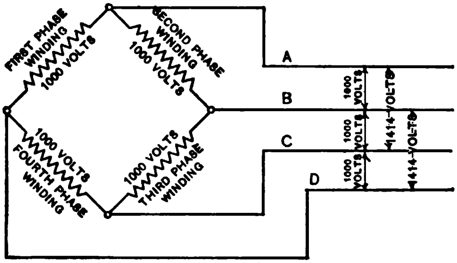

FIRST PHASE WINDING 1000 VOLTS
SECOND PHASE WINDING 1000 VOLTS
1000 VOLTS FOURTH PHASE WINDING
1000 VOLTS THIRD PHASE WINDING
A
B
C
D
1000 VOLTS
1000 VOLTS
1000 VOLTS
1414 VOLTS
1414 VOLTS

FIG. 143.—Four-phase System; Voltage Between Lines.

affairs. The diagram is descriptive in that it gives the value in volts of each phase winding. The total produced in this respect is 1,000 volts from each, but the resulting pressure is not 2,000 from two situated 90 degrees apart, but 1.414 × that of one. The data resulting from this examination indicates the presence of two distinct voltages in the line, which might be arranged for inspection as follows:

First—Between lines A and B, 1,000 volts, or the difference of potential produced by the second-phase winding, with which the outgoing circuits connect.

Second—Between lines B and C, 1,000 volts, or the difference of potential produced by the third-phase winding, with which the outgoing circuits connect.

Third—Between lines C and D, 1,000 volts, or the difference of potential produced by the fourth-phase winding, with which the outgoing circuits connect.

Fourth—Between lines A and C, 1,414 volts, or the difference of potential produced by the second- and third-phase windings, equal to $\sqrt{2} \times 1{,}000$ as given.

Fifth—Between lines B and D, 1,414 volts, or the difference of potential produced by the third- and fourth-phase windings, equal to $\sqrt{2} \times 1{,}000$ as given.

It may be mentioned in connection with this statement of the facts that the differences of potential noted in the fourth and fifth cases may also be regarded as coming from the first and fourth phases in the fourth case, and from the first and second phases in the fifth case. On this basis the two pressures found in a system of this kind are respectively 1,000 and 1,414 volts.

Amperages in a Star- and Mesh-connected Two- or Four-phase System.—The value of the amperes in the two circuits called mesh and star two or four phase may be obtained by realizing, that whenever two-phase currents are co-operating, such as the two found between the second- and first-phase windings in a mesh-connected two-phase system, the line wire connected to that point will carry a current which is not equal to their sum but to a value represented by $\sqrt{2}$ times the current in either of these windings. On this basis both the star- and mesh-connected two-phase armatures differ, as far as the respective values of their currents and electromotive forces are concerned, in a manner readily understood in the light of the following tabulation of these values:

First—Amperes in the line wires of a star-connected two-phase system, sometimes called a four-phase system, are equal to the amperes in any one of the coils.

Second—Amperes in the line wires of a mesh-connected two-phase system, sometimes called a four-phase system, are equal to $\sqrt{2} \times C$, or $1.414 \times C$, where C is equal to the current in amperes in any coil. It is not a difficult matter to present the difference between the two ways of connecting up the two-phase armature, as far as the volts and amperes are concerned, particularly in a case where they are of equal capacity, by stating that the amperes in the terminals of any phase winding of a star-connected armature remain the same, but the volts in the line are equal to $\sqrt{2}$ or 1.414 times the volts developed by any given coil generating one phase. On the other hand, the amperes in the line connecting to any one phase, where there is a mesh-connected armature, are not equal to the current in the coils of any one phase, as in the first case, but equal to $\sqrt{2}$ times the amperes in any one phase, or $1.414 \times C$, as stated. But the volts remain the same in the line wires as those generated by the coils of any phase. Thus, volts and amperes differ in the two- and three-phase star- and mesh-connected armatures, as far as the line wires are concerned which carry their energy, in a manner which makes it possible to readily grasp the value of these elements of power. A recapitulation is therefore presented for purposes of reference in the following systematized form:

Line wires carry the power of a	Volts.	Amperes.	Power.
Single-phase armature...........	Same as armature.	Same as armature.	E×C× power factor.
Two-phase star-connected armature...........	Volts of one winding × $\sqrt{2}$.	Amperes same as those of one coil.	$\sqrt{2}$ × E × C × power factor.
Two-phase mesh-connected armature...........	Same as those of one coil.	Amperes of one coil × $\sqrt{2}$.	$\sqrt{2}$ × E × C × power factor.
Three-phase star- or Y-connected armature......	Volts of one coil winding × $\sqrt{3}$.	Amperes same as those of one coil.	$\sqrt{3}$ × E × C × power factor.
Three-phase delta- or mesh-connected armature	Volts the same as those of one coil.	Amperes of one coil × $\sqrt{3}$.	$\sqrt{3}$ × E × C × power factor.

From a survey of the table, it is evident that both the two- and three-phase systems may be calculated for volts and amperes in the line wires, by using either the $\sqrt{2}$ or the $\sqrt{3}$ as the coefficient. For instance, if an armature coil, by which is meant one of the distinct windings, carries a certain amperage and voltage, the amount of either of these power elements received by the line is determined by the number of phases generated and the system of armature connections employed. The results of such an experiment can be readily compared in the following estimate, based upon a given winding:

WINDING PRODUCING 1,000 VOLTS AND 100 AMPERES.

	Volts.	Amps.	Power =
Single-phase armature...	1,000	100	100×1,000× power factor.
Two-phase star-connected armature......	1,414	100	100×1,414× power factor.
Two-phase mesh-connected armature......	1,000	141.4	141.4×1,000× power factor.
Three-phase star-connected armature	1,732	100	100×1,732× power factor.
Three-phase delta-connected armature......	1,000	173.2	173.2×1,000× power factor.

The total of power obtained from the line wires respectively may be readily determined by a consideration of the power output of the various generators from which the power is obtained. The totals, it will be noted, are the same for the two-phase armatures. The totals are also the same for the two three-phase armatures. The relative amounts of power with the same power factor would therefore be represented by the products obtained from the last column, or 100,000 × ϕ, where ϕ is the power factor for single phase; 141,400 × ϕ for two-phase star; 141,400 × ϕ for two-phase mesh; 173,200 × ϕ for three-phase star; and 173,200 × ϕ for three-phase mesh.

Comparison of the Copper Required for Different Systems.—To further accentuate the difference between one system and another, including the direct current, the amounts of copper have been calculated in a case where the conditions are equal. By this is meant that the same amount of power is transmitted over equal distances at equal differences of potential between line wires and at the same line loss. The heading of the table, prepared by Rhodes of England, will be sufficiently explanatory for all practical purposes.

COMPARISON OF THE AMOUNTS OF COPPER REQUIRED FOR LINE WIRES FOR TRANSMISSION OF THE SAME AMOUNT OF POWER AT THE SAME LINE VOLTAGE OVER EQUAL DISTANCES AT THE SAME EFFICIENCY:

	Pounds of copper.
Direct Current—the line long enough to require..	1,000
Single phase....	1,000
Two phase four wire....	1,000
Two phase three wire....	729
Three-phase mesh or delta connections....	750
Three-phase star or Y connections....	750

According to these figures, the two phase is the cheapest when using only three wires. The three phase remains the same as far as weight of copper is concerned, whether it is connected one way or the other. The governing factor, however, would be the line pressure, which it is evident, as a matter of insulation, would be of equal if not greater importance than the question of the weight of copper employed.

Two-phase Four-wire System with Transformers.—In the illustration (Fig. 144) the method of con-

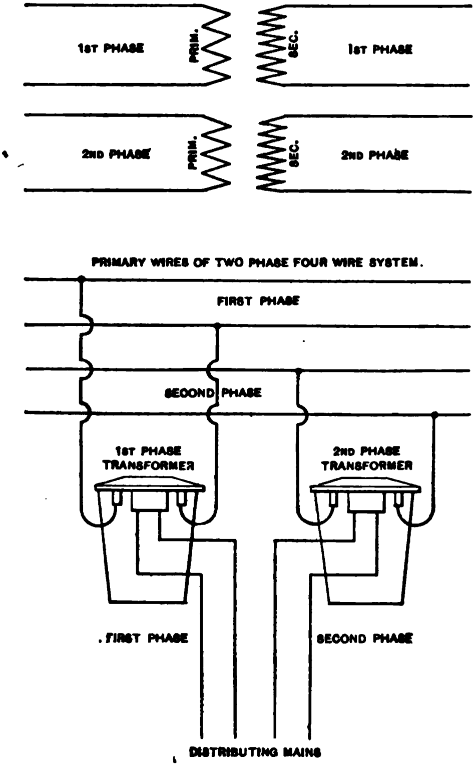


FIG. 144.—Method of Connecting Transformers to a Four-wire Two- or Four-phase System.

necting up transformers to a four-wire two-phase system is shown. The first and second phases are distinct in the sense that they are transformed independently of each other in separate transformers, and then the lines are continued as before. The only difference is that of the pressure of the power lines before and after the transformation. The pressure may be raised or lowered, though no material difference results. The only point to be noted in a system of transformation is whether it is carried out in such a manner that the final transformer connections lead to a three-wire instead of a four-wire system, as before.

Two Phase Four Wire to Two Phase Three Wire.—The method of connecting up transformers so that a four-wire two-phase system is changed into a three-wire two-phase system is given in the illustration (Fig. 145). The noteworthy feature here is the connecting together of two transformers and tapping from this junction to the main. Each transformer as before takes its individual phase, as shown in the system of connections in the upper part of the sketch. The transformation of the pressure is in no way effective in modifying the relative position of the phases. The first phase and then the second phase operate consecutively, producing in the line wires the same currents as those originally passing through the four wires. The drop in copper, according to the table given, is from 1,000 to 729 pounds by this change in system.

Three-phase Three-wire Delta.—The use of three distinct and independent transformers is indicated in the sketch (Fig. 146), which shows the manner

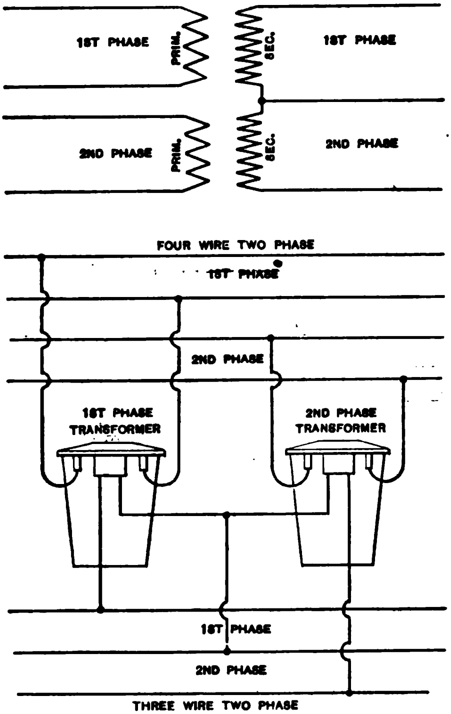


FIG. 145.—Transition from a Four-wire to a Three-wire Two-phase System.

of connecting up such devices for purposes of raising or lowering the pressure. The delta system of connections has been carried out, as may be readily ascertained by a brief examination of the sketch embodying the idea involved. The first-phase transformer connects the line wires 1 and 2. The primary and secondary of this transformer are indicated

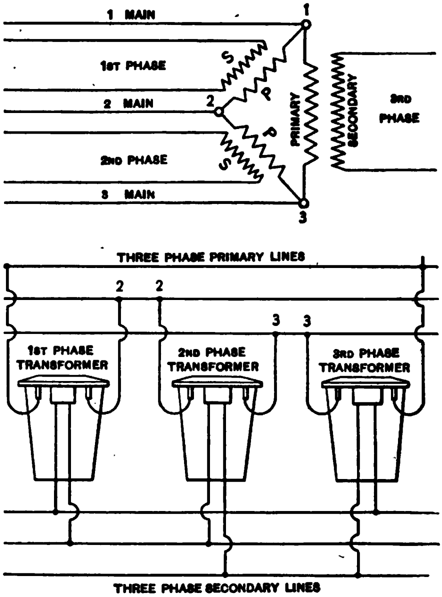


FIG. 146.—Transformers Connected to Each of the Three Phases, Delta Connected.

in the theoretical sketch, as well as those of the transformer of the second phase connected to line wires 2 and 3, and the transformer of the third phase connected to line wires 1 and 3. Although the upper sketch would seem to show, as far as the transformers are concerned, the existence of six wires, it is easy to see that they belong to the three wires below connecting to the three transformers in position. The saving in copper in this case is that represented by the difference between 1,000 for direct current or two phase four wire and 750, the figure for this system. The fact that a single-phase and a direct-current line, of equal pressure and current, require equal quantities of copper is more in favor of the direct than the single phase, disregarding the ease and cheapness of transformation. An alternating-current system possesses distinct advantages over a direct, found mainly in the use of the transformer for stepping low pressures up and high transmission pressures down.

Three Phase Three Wire Y or Star Connected.—The connections of a three-wire three-phase circuit are shown in the illustrations (Fig. 147) with respect to the linking together of the line wires to the distributing wires through the medium of the transformers. The three transformers are connected together in the star fashion, as may be discovered by tracing their connections from the transmission lines. In the case presented the primary wires feed into the primaries of the three transformers from the lines 1, 2, and 3 to the primary terminals 1, 2, and 3. The other three ends are connected together at the common junction J, as shown in the sketch. The three secondary windings of the transformers are also connected up in a similar manner. One terminal from each is run down to the three distributing wires, which are also numbered 1, 2, and 3. The other terminal from each respectively is brought to a point where K marks their common

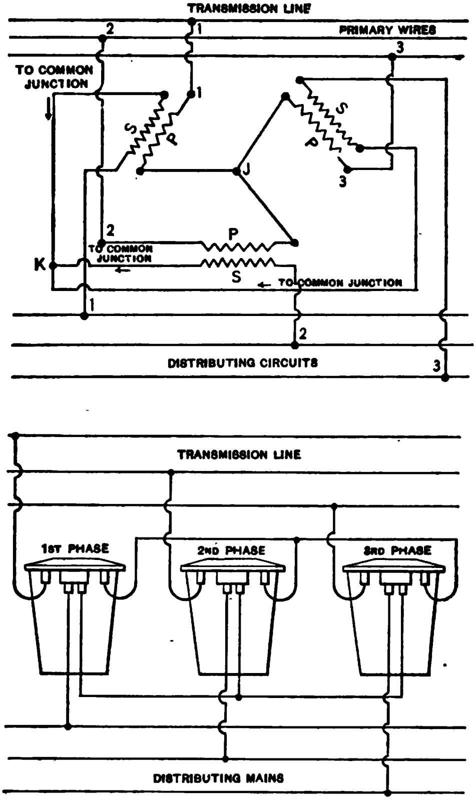


FIG. 147.—Three-wire Three-phase Star Connection for Transformers.

connection. The case thus presents itself of three lines above and three lines below, with three transformers in between, so to speak, consisting of six coils all together. Three of these coils, the primaries of the transformers, are joined according to the star system, as far as a corresponding end from each is concerned. The other three ends as described tap into the transmission wires. The same is virtually true of the other three coils, which are joined as well, according to the star connection, as far as three of their individual ends respectively are concerned. The other three ends feed the main lines at a reduced pressure in the manner shown in either of the two sketches representing this idea. The particular point to be noted is that only one transformer is utilized for each phase. Thus the first, second, and third phases pass into and out of the self-same transformers, thus simplifying the process of transformation, as well as the method of generation and transmission.

Combination Y and Delta.—When three phase is being used for purposes of light, heat, and power, the three transformers can be connected up in a manner which represents a combination of the star or Y and the delta idea. This is also done in a simple manner by connecting the primaries of the transformers according to the Y or star principle, and the secondaries according to the delta or mesh system. The method may be reversed, and the primaries connected up according to the delta, and the secondaries according to the Y principle. There are certain systems or modes of connection possible, based upon the fundamental ideas represented by the phase relationships and the use of two or three transformers. If only two transformers are used in three-phase transmission and distribution, it will be necessary to use the delta idea, carrying it out as though there were three transformers instead of two. But an arrangement of this kind would mean much larger transformers than before. The increase in size in this case would be in the ratio of 1 to 1.75; or in the case of three 100-kilowatt transformers, such as might be used, the change to two transformers would mean a capacity of 175 kilowatts apiece instead of the original figure. On this basis, it is evident that if three 100-kilowatt transformers are required to transmit a given quantity of power, a change to two transformers necessitating the use of 350 kilowatts in total capacity means an increase over all of 50 kilowatts. For this reason the use of two instead of three transformers is not a gain but a loss, as far as the total capacity required is concerned. The other standpoint to take, however, is the one that opens up the inquiry as to whether it will or will not cost more to manufacture three 100-kilowatt transformers than two of 175 kilowatts. In addition, it might be asked whether the efficiencies would be such that the cost of wasted power is not less in the two larger than in the three smaller transformers.

Changing Two Phase into Three Phase.—A method of phase transformation has been devised by means of which a two-phase current can be transformed into a three phase. It is accomplished by the use of two specially wound and constructed transformers whose connections are made according to the sketch (Fig. 148). The primaries of these transformers, as shown, are connected directly with the alternator terminals. The alternator, it is needless to state, is a two-phase machine. The potential it develops is not very high, and for that reason the ratio of transformation is in favor of the outgoing line wires A, B, C. The sketch shows how the currents proceed, the first phase entering the lower primary coil of the first transformer, and returning from it to the alternator, as indicated. The second phase enters the upper coil, and completes the circuit from the alternator to the brushes 2, 2. Thus the first phase leaves brushes 1, 1, to enter the primary of the transformer, whose secondary is tapped

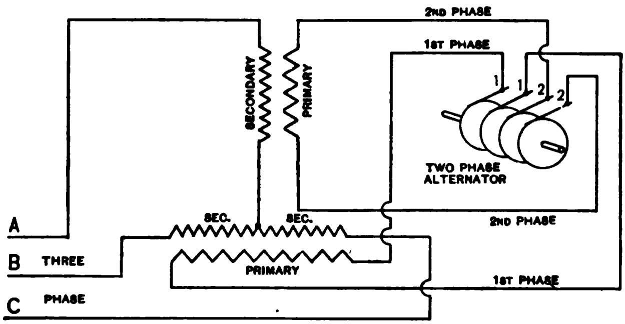


FIG. 148.—Changing Two Phase into Three Phase.

in the middle, J. The second phase leaves the brushes 2, 2, and passes through the primary of the transformer, whose secondary remains in a sense untouched. This condition of affairs presents the following facts: The secondary tapped in the middle at J may have, say, 100 turns; this would mean 50 on each side. The other secondary has only 87 turns, which means that the calculation of this particular number of turns is based upon the estimate that its turns must equal $\sqrt{3} \times 50 = 1.732 \times 50 = 86.6$. In other words, if the simple rule is adhered to of making the turns of the two secondaries, which, of course, become three through the middle tap to one, observe the arithmetical conditions, that one-half the turns of one secondary be multiplied by the $\sqrt{3}$ to give the turns of the other secondary; the transformer for not only transforming the pressure if necessary, but the phase as well, may be constructed along the general lines of the diagram, which gives the connections of such a system.

A Complete Phase-and Pressure-Transforming System.—The general conditions governing the generation, transmission, and distribution of electricity may be entirely embraced by the outlines of a system, involving the idea of not only transforming the pressures to values deemed more serviceable, but transforming the two or quarter phase (Fig. 149), as it is sometimes called, into three phase. The entire sketch shows the development of the process from its beginning to its end, as far as the actual power generation and light production are concerned. The steps to be considered are several, and may be noted as follows as they appear: First, the generation of the currents from a two-

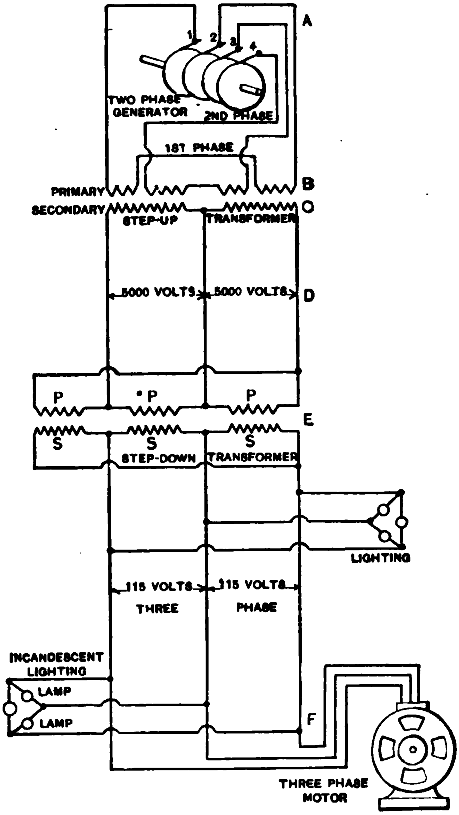


FIG. 149.—Transformation of the Pressure and Phase of a Two- into a Three-phase Current.

phase machine; second, the passing of this two-phase current into the primaries of transformers constructed in such a manner that, though the two phases remain the same, they do not issue after transformation the same, but as three distinct phases; third, the transformation of the pressure upward to a point or value fit for transmission; fourth, the conduction or transmission of the power from the generating to the receiving or distributing point; fifth, the further transformation of the pressure downward to suit the practical necessities of lighting and power; and finally as sixth, to utilize the electricity then obtained at low pressure to serve its originally intended purpose—either the running of motors or the lighting of arc or incandescent lamps. These stages in the process of generation, transformation of phase and pressure, transmission, transformation to a lower pressure, and utilization of the power for lighting are represented at points at which they occur by the letters A, B, C, D, E, F, as may be noted. The two phases, proceeding from brushes 1, 2, 3, 4, are directed into the transformer which receives them, and their path may be traced in the coils as indicated. The tapping of the receiving end of the circuit is readily accomplished for the supplying of either motors or lamps with such power as they may require, if adapted to this system.

Changing Two Phase into Three Phase and Back into Two Phase.—The reversal of the system is as necessary to know as the method to be employed to originally transform the phase. For instance, the changing of two-phase currents into three phase as described may represent a case where the retransformation is just as necessary. For that reason a system of connections is shown in which the change back to two phase is possible. This is accomplished by making use of practically the same elementary method as in the former case. The generator terminals are connected to the primary terminals of the transformer so as to reduce the resulting phases into a series, which follow one another according to the same schedule as a regular three-phase current. The various steps in the process are noted by means of the letters A, B, C, D, E, and F. The first process is that of generation as before, denoted by A; the second process, that of transformation of phase and pressure, shown by B and C. The sketch (Fig. 150) shows the analysis or division of the system into three parts, called the two-phase generating and transforming section, in contradistinction to the transmitting three-phase and the transforming two-phase section. At D, according to this, the three-phase transformation is emphasized to the exclusion of all else. At E the primaries and secondaries of the transformers are so related that the pressure and phase are changed. This is also accomplished at B and C in the first place. The circuits at E and F in the two-phase section are then so developed that the first section is practically reproduced and the current issues in its original form, namely, a two phase, suitable, as indicated, for lighting, etc. The flexibility of the system is one of its most important features, aside from the practical service it renders.

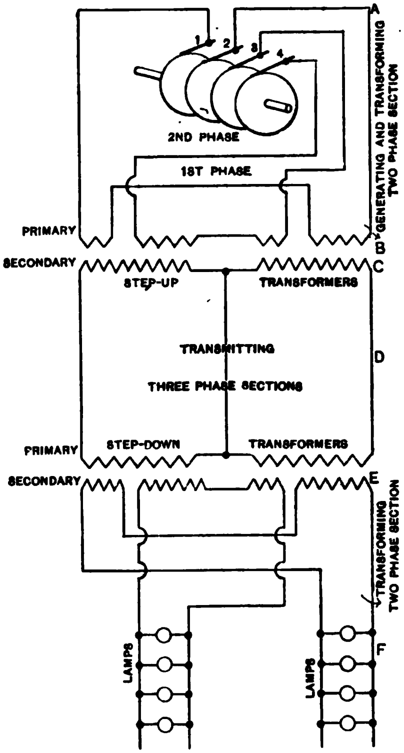


FIG. 150.—Changing Two Phase into Three Phase and then Back into Two Phase.

The transformation of the phase from two to three and the reverse will serve no useful purpose unless a distinct economic gain is made; if so, it is hardly necessary to state that the change is recommended.

Features of Transformer Design.—The important features of transformer design are really the elements which collectively give it value as an efficient and durable piece of apparatus. The alternating current is so closely associated in an engineering sense with the direct use of the transformer that a brief reference to its first and most important requirement will be of interest. In this respect, the demand of practice is that the voltage shall remain constant with all changes of load. By this is meant the voltage of the secondary. Summarizing this important feature with the causes operating against its best development will give the following:

Causes Operating to Prevent the Development of a Constant Potential at the Terminals of the Secondary.—First, a very large primary magnetizing current or too much current in the primary coil; second, a very large internal resistance for the secondary coils of the transformer; third, excessive magnetic leakage in the transformer. It is possible to greatly reduce the leakage by having an excellent magnetic circuit, and running the iron at a low induction per square inch. The other feature of great importance is naturally the heat of the coils. Thus, a recapitulation would show that the preservation of a constant potential at the secondary terminals is an implied necessity in a transformer built for this purpose. It would also show the necessity for keeping down the temperature to a normal value.

And, in addition, it is obvious that the insulation of the transformer must be able to meet a very high test. On this basis, transformer design, as outlined, means a constant potential with all normal variations of load; a limited temperature under the same conditions; a reliable degree of insulation; and finally a reasonably high efficiency. The up-and-down transformation of pressure and the change of phase from two to three, or three to two, mean in every case transformers whose action is a recommendation to further use; otherwise our alternating-current systems, however perfect in theory, would fail when put into operation.

CHAPTER XIV

FEATURES OF TRANSFORMER TESTING.—LOAD OF TRANSFORMERS.—VOLTAGES OF TRANSFORMERS.—LIGHTING AND POWER TRANSFORMERS.—TRANSFORMER CONNECTIONS. — LIGHTNING DISCHARGES. — PRIMARY WINDING.—SECONDARY WINDING.—HANDLING THE TRANSFORMER.—SIZES, WEIGHTS, AND OIL REQUIRED. — THE SINGLE-PHASE INDUCTOR ALTERNATOR.—THE ROTOR OF THE INDUCTOR ALTERNATOR.—FREQUENCY OF THE ALTERNATIONS.

Features of Transformer Testing.—One of the most important of all questions in alternating-current work is the question of insulation. Efficiency and insulation are frequently correlated, but it is obvious that one of the leading features in any testing to which transformers or any other apparatus may be subjected is a form of testing which immediately betrays weakness in the insulation. For this reason an outline of the practical test to which transformers particularly are subjected is given as follows:

First—A run at overload with the normal potential. By this means any inherent defects are quickly made apparent in the entire device, without any possible destruction to it, as might happen with a severer test.

Second—A run at three times the normal voltage without any load. By this means the insulation is tested in a fair way, and developing defects are rapidly exaggerated and made evident without delay.

Third—An insulation test of 8,000 volts between the primary and secondary.

Fourth—An insulation test of 6,000 volts between the primary and the iron.

Fifth—An insulation test of 4,000 volts between the secondary and the iron.

Because it is the rule and not the exception for transformer coils to be immersed in oil, a test such as outlined is best made without oil. The reason for this is not hard to detect, because it lies in the fact that defective insulation becomes far better in oil, and is therefore hidden to an extent that makes it undetectable. As far as the actual pressure obtained from the secondary is concerned, it is always best in practical testing to run this up to six or eight times its normal value, if only for a very short time. It is not always the immediate faults that count, but those which lie hidden, as stated before, and which will either subsequently develop or appear at once under the immense potential strain considered temporarily advisable. A knowledge of the iron loss and the efficiency in general then means the determination of the proper value of the transformer.

Load of Transformers.—When referring to the general efficiency of transformers, it must not be forgotten that there are other efficiencies than those which might be ordinarily accepted as a true measure of their values respectively. By this is meant that the all-day in contradistinction to the full-load efficiency is the matter of importance in the operation, and necessarily in the financing of light, heat, and power problems commonly included within the scope of central-station and power-transmission plants. Therefore it may be said that there are several efficiencies to a transformer, such as the quarter-, half-, three-quarter-, and full-load efficiency. It is, however, very evident that the transformer, as a part of a large generating plant, is better designed to have a high general than a high specific efficiency. In other words, given two transformers for station service, that one is the better as a money maker which possesses the highest general efficiency as compared with the other one, which for the sake of argument may be considered as possessing a high efficiency only at a given point of load, such as half, three-quarter, or full load.

Voltages of Transformers.—What is meant by the voltages of transformers is simply the fact that practice has dictated a custom of an extremely valuable nature of winding them for two primary and two secondary voltages. Some manufacturers even wind for two primary and three secondary voltages. In other words, it is quite evident, after a little contemplation of the subject, that the greater the range of application of the transformer, the greater the serviceability in general electric-light and power practice. A certain design made by the Westinghouse Company, called the O. D. type, has a series of interesting features in this respect (Fig. 151) combined in its construction. Transformers up to and including the 3-kilowatt size are wound for 1,050 and 2,100 volts, and for 52½, 105, and 210 volts. Larger sizes (Fig. 152) are wound for the same primary voltages, and with secondaries for 52½, 105, and 210 volts, or for 105, 210, and 420 volts. A dis-

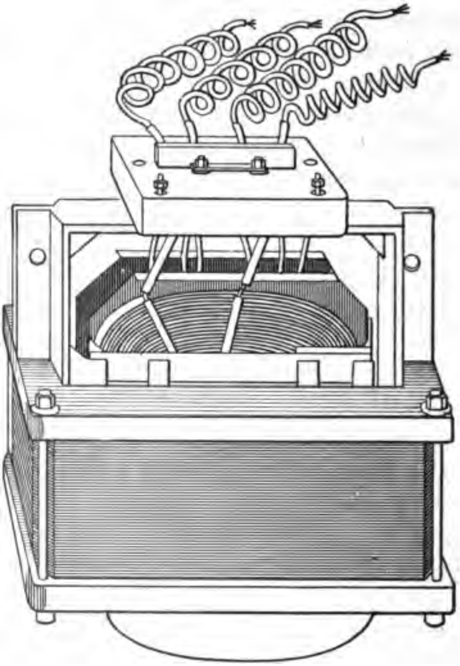


FIG. 151.—General Construction of the Smaller Size Transformer.

tinction thus arises which has been, both in theory and practice, the cause of a classification denoting a difference between what are called lighting and power transformers.

Lighting and Power Transformers.—Transformers of the type outlined are called lighting or power transformers on the following basis: If the transformers have secondaries for 52½, 105, and 210 volts,

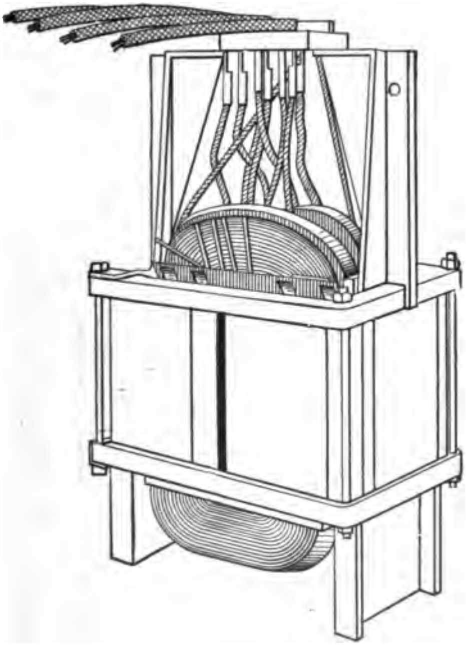


FIG. 152.—General Construction of a Large Oil Transformer.

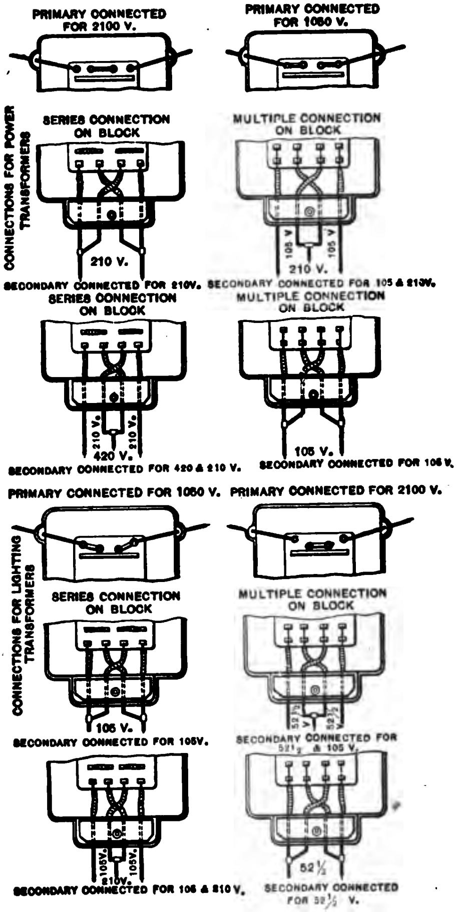

PRIMARY CONNECTED FOR 2100 V.
PRIMARY CONNECTED FOR 1050 V.
CONNECTIONS FOR POWER TRANSFORMERS
SERIES CONNECTION ON BLOCK
MULTIPLE CONNECTION ON BLOCK
210 V.
105 V
105 V
210 V.
SECONDARY CONNECTED FOR 210V.
SECONDARY CONNECTED FOR 105 & 210V.
SERIES CONNECTION ON BLOCK
MULTIPLE CONNECTION ON BLOCK
210 V.
210 V.
420 V.
105 V.
SECONDARY CONNECTED FOR 420 & 210 V.
SECONDARY CONNECTED FOR 105 V.
PRIMARY CONNECTED FOR 1050 V.
PRIMARY CONNECTED FOR 2100 V.
CONNECTIONS FOR LIGHTING TRANSFORMERS
SERIES CONNECTION ON BLOCK
MULTIPLE CONNECTION ON BLOCK
105 V.
52½ V
52½ V
SECONDARY CONNECTED FOR 105V.
SECONDARY CONNECTED FOR 52½ & 105 V.
105V.
105V.
210V.
52½
SECONDARY CONNECTED FOR 105 & 210 V.
SECONDARY CONNECTED FOR 52½ V.

FIG. 153.—Connections of Transformers.

they are known as lighting transformers. If they have secondaries for 105, 210, and 420 volts, they are known as power transformers. Central stations are modifying their practice so rapidly that many of them that are now supplying 52½- and 105-volt lighting circuits are about to install or have already installed three-wire systems with 210 volts across the outside wires. In consequence, transformers wound for 52½-, 105-, and 210-volt circuits may be readily used for such service without any extra cost for new apparatus. This is readily accomplished by means of a change in the secondary connections. A series of illustrations (Fig. 153) showing the connections necessary in both power and lighting transformers are given with such data as are necessary for a full understanding of the character of the advantages gained. Examination of the sketches will show a variation in the connections by which the voltages of the primaries and secondaries can be changed to suit such new conditions as practice imposes. The technical value of this method as a part of the manufacturing as well as the lighting industry requires little or no recommendation, as it is, as it appears, an immense advantage over the original practice of using transformers of fixed pressures. There are several cases presented:

POWER TRANSFORMERS

First—A primary connected for 2,100 volts, and a secondary connected for 210 volts.

Second—A primary connected for 1,050 volts, and a secondary connected for 105 and 210 volts.

Third—A secondary connected for 210–420 volts, and a secondary connected for 105 volts.

LIGHTING TRANSFORMERS

Fourth—A primary connected for 1,050 volts, and a secondary connected for 105 volts.

Fifth—A primary connected for 2,100 volts, and a secondary connected for 52½ and 105 volts.

Sixth—A secondary connected for 105–210 volts, and a secondary connected for 52½ volts.

Transformer Connections. — Connections once made by soldering are now almost entirely dispensed with in the primary coils through the general use of screw and link connections. The soldered connections are formed on the secondary, however, more because of the very heavy current passing there, which develops a certain risk with screw and link contacts, than for any other reason. As far as convenience is concerned, the original practice of soldering and unsoldering the primary connections of transformers was one of the worst features in daily practice. As the transformers are all oil protected, it is evident that the oil can leak out wherever an outlet protrudes, entirely through the conductor's insulating covering acting as a wick. To avoid this, a porcelain terminal block is used (Fig. 154), into which the wires are inserted with their insulation removed. A sketch of the block is shown as manufactured for this purpose, with the various terminal wire holes in evidence.

Lightning Discharges.—Oil has other advantages than those of merely filling up questionable interstices in the insulation or reinforcing it for ordinary purposes. When lightning strikes a station, the oil transformers are the pieces of apparatus that must be protected at all hazards, or the whole system will be destroyed. Oil is therefore the determining influence in many cases (Fig. 155), which either holds the station as a source of light and power intact during the possible catastrophe or permits it to be put out of commission. A flash of high-potential static electricity possesses an ability to start an arc without any difficulty between two high-potential wires. To avoid this as far as possible, oil is used in so far as it is apt to prove an aid. Between coils of high potential, its use is unquestioned; it is, in fact, absolutely necessary. The dry transformer, except

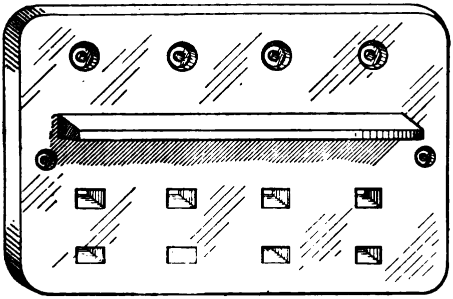


FIG. 154.—Porcelain Terminal Block.

for very small sizes, is a thing of the past, for reasons of general insulation and lightning in particular. A transformer's resisting power to the effects of lightning is largely a matter of the oil immersion, other things being equal; the more oil, in a sense, the more insulation and protection.

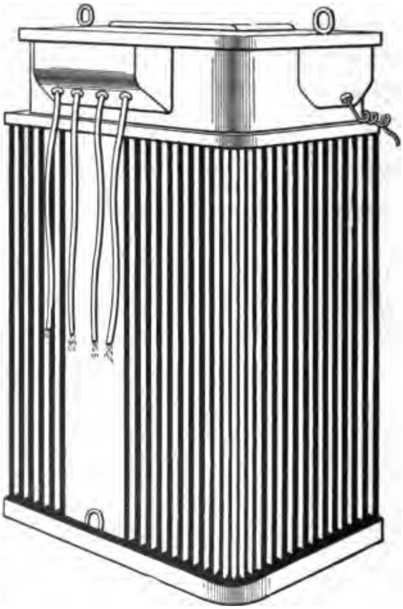


FIG. 155.—Transformer in Corrugated Oil-filled Case.

Primary Winding. — An interesting practice in connection with the construction of the primary coils is the fact that they are so wound that when complete they consist of many layers. There are two reasons for this, which might as well be called one reason. The first is the advantage of subdividing the pressure as much as possible, and the second that of diminishing the strain upon the insulation as far as consecutive layers (Fig. 156) are concerned. A transformer whose primary is built up of 50 or 100 layers of a few turns per layer is by far a safer transformer to use than one consisting of only a few layers of a great many turns apiece. In this respect it may be said that primary-coil construction has advanced to a remarkable degree in the hands of leading manufacturers.

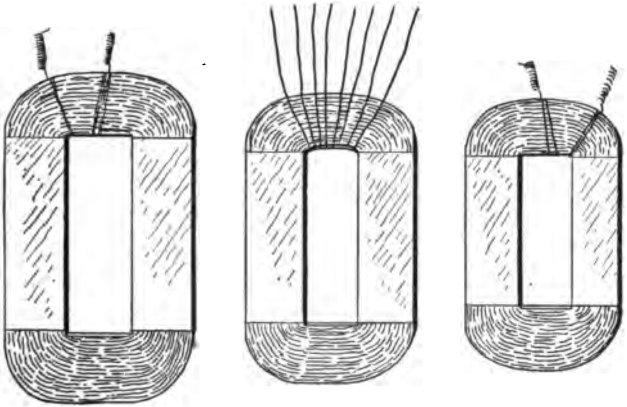


FIG. 156.—Coil Winding of Many Layers.

Secondary Winding. — The secondary coils are solid and compact, being wound with square wire in the particular type described. The use of wire of square cross-section necessarily implies a difference which may be represented as that existing between the value 70 and 100, in comparison with round wire and in favor of square wire. Where coils, as in this case, are wound in many layers, the use of a square instead of a round wire opens up advantages not only in radiating surface, which is greatly increased, but in a lower resistance as well. Both of these features are beneficially cumulative for the reasons that, first, a greater radiating surface, other things being equal, means a lower operating temperature, and consequently a higher efficiency; and, second, a lower resistance means less waste of power in watts, and naturally a lower temperature and a higher efficiency. The ends of the coils are spread apart where they extend beyond the iron, thus increasing the air ventilation and the exposed coil surface to radiation. Transformer design, like motor and dynamo design, is thus seen to be an effort to develop a device which will perform the functions for which it is built, on the one hand, and preserve a reasonably low temperature, on the other hand.

Handling the Transformer.—To handle the transformer, corrugated iron cases are employed. The corrugations, it is unnecessary to state, are a means of securing a greater radiating surface. The tops and bottoms are made of cast iron. All sizes of transformers are made in such a manner that they will not deteriorate with outside service, and for this reason they must be made weatherproof. In the illustration (Fig. 157) the manner of lifting the

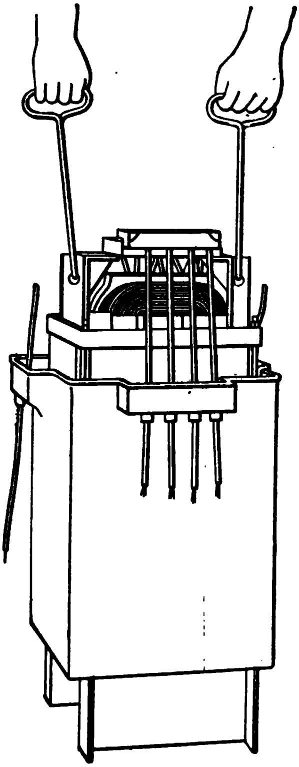


FIG. 157.—Method of Lifting the Transformer Out of the Oil.

transformer out of its case is shown. Two irons with handles and hooks, which engage with a hole on each side of the supporting case of the transformer itself, are used. In this respect, it may be mentioned that the examination of the transformer, or a renewal of the oil, makes this very simple feature of construction an absolutely essential element.

Sizes, Weights, and Oil Required.—Taking a table of manufactured transformer sizes as a standard, they may be presented for inspection as follows:

Capacity. Kilowatts.	Secondary Voltage.		Weight. Net.	Weight. Gross.	Gallons of Oil.
	Lighting.	Power.			
¼	52½ to 105 to 210		55	76	1
½	“		73	93	1
1	“		126	167	2
1½	“		138	170	2
2	“		146	180	2
3	“		194	245	3
4	“	105 to 210 tc 420	231	290	4½
5	“	“	348	440	4
7.5	“	“	494	625	7½
10	“	“	515	645	7
15	“	“	844	940	18
20	“	“	936	1,185	27
25	“	“	1,062	1,340	26
30	“	“	1,121	1,450	35
37.5	“	“	1,220	1,570	34
50	“	“	1,420	1,800	40

These transformers, in common with others of standard makes, may be applied with certain modifications to two- or three-phase transformation. In addition, it may be understood that those for very high-tension service do not differ essentially in construction from those just described.

The Single-phase Inductor Alternator.—There are many subdivisions of alternators, such as those denominated single, two, and three phase, as regards

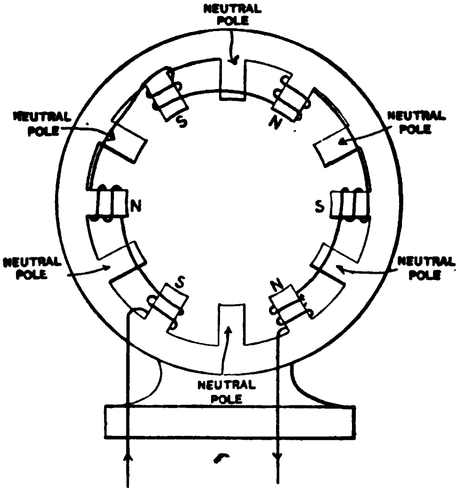


FIG. 158.—Winding of Single-phase Inductor Alternator Field, Showing Neutral Pole.

their form of output. But the particular class called inductor alternators represent a distinct construction, due to the elimination of the marked difference between the field and armature. It is not to be understood from this that the field and armature are other than those combined in the type of single phase to be described, which justifies this assertion. This combination occurs in the following manner: The outer frame is cast with a series of inwardly pointing poles, as illustrated (Fig. 158). These poles are so wound that every first, third, fifth, etc., is supplied with a coil which magnetizes it as if it were part of the field of a direct-current generator. Under these conditions a neutral pole may be found between every two magnetized poles. This is the feature referred to as representing a combination of the two elements in one part of the machine, for the reason that the neutral poles are used (Fig. 159) as the means of generating electromotive force. They

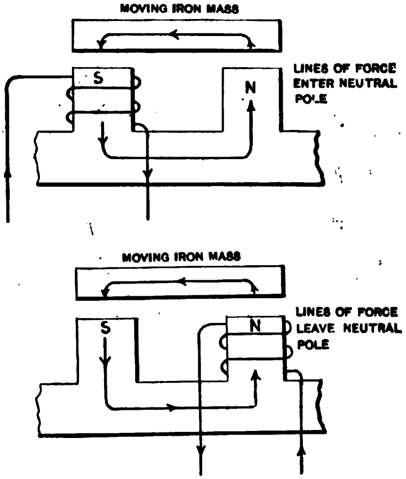

MOVING IRON MASS
S
N
LINES OF FORCE ENTER NEUTRAL POLE
MOVING IRON MASS
S
N
LINES OF FORCE LEAVE NEUTRAL POLE

FIG. 159.—The Way the Lines of Force are Made to Pass Into and Out of the Neutral Poles.

thus serve to take the place of the armature as generally understood in the following manner: If a mass of iron is rotated within the field thus produced, it is very evident that its movement past the consecutive poles will, if it is long enough to bridge two, cause the lines of force to magnetize each neutral pole twice in opposite directions. The meaning of this is that the lines of force move rapidly back and forth into and out of the neutral poles as the iron mass swings past them. The theory of this action is shown in the sketch, and merely represents the case of a moving armature, directing the lines of force of successive poles into the otherwise neutral poles in regular order. The conditions created by this state of affairs are best understood by reference to the fundamental principles of electromotive force, and the case of lines of force moving in and out of a coil of wire. In other words, if coils are placed on these neutral poles (Fig. 160), they will be exposed to the effects of the back-and-forth movement of the lines of force. A little consideration will show no difference between this state of affairs and a primary or secondary coil of a transformer, except in so far as they are made to serve a different purpose. The secondary, however, is a generator of E.M.F. by means of lines of force passing in and out of it. The mere fact of its developing a higher or lower E.M.F. than the primary is entirely a question of the ratio ot the two windings. In the case of a rod of iron carrying a coil, and systematically magnetized one way and the other, the turns composing the coil interlink with the lines of force at a certain high rate per second. The principle involved is therefore that of a certain number of turns interlinking with

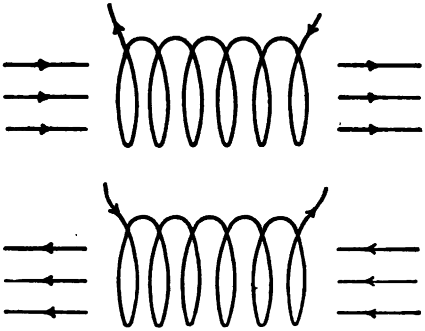


FIG. 160.—The Two Directions of the Lines of Force Producing Reversing Currents.

a certain number of lines of force at a certain specific rate. The case may be regarded as one in which 1,000,000 lines of force are employed; 1,000 turns per coil; and the change of polarity occurs at the rate of 20 per second. The proposition thus indicates the effect produced by an interlinkage equal to 1,000 × 1,000,000, or 10^9, per twentieth of a second. As 100,000,000 interlinkages per second are equal to one volt, it is evident that 10 times that number per second would equal 10 volts. But the time taken is only one-twentieth of a second, therefore the volts produced $= 20 \times 10 = 200$. A number of these stationary generating coils on a series of otherwise neutral poles would mean a total pressure per movement of the lines of force equal to the pressure of one multiplied by their number. For instance, in the illustration (Fig. 161) there are six coils acting in the capacity of armature inductors, each generating 100 volts. The total is therefore equal to 6 × 100 = 600 volts.

The Rotor of the Inductor Alternator.—The revolving iron mass is called the rotor, and consists of a series of segments of iron as indicated in the sketch (Fig. 161) by the letters C, D, E, G, H, K.

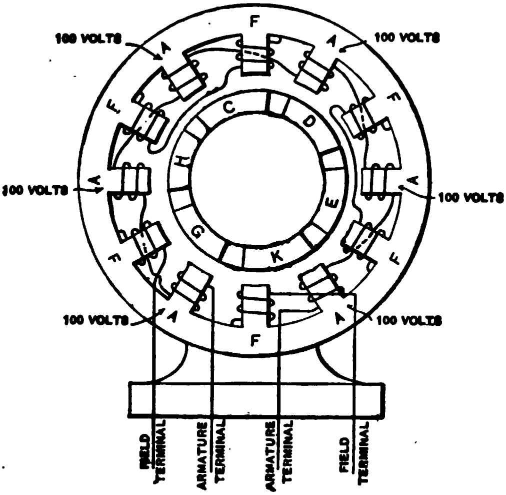


FIG. 161.—Frame with Field and Armature Windings in Place.

With this arrangement of a double function performed by the frame, both as a provider of the field and a generator of electromotive force, the rotor resolves itself down to a revolving mass which serves to send the lines of force back and forth through the poles. Each iron segment is wide enough to cover two poles, and is made of laminated wrought iron. The segments are bolted together (Fig. 162), and then secured to the frame composing the armature. The rapid movement of the segment means a rapid reversal of the lines of force through them, and in consequence the development of hysteresis and eddy currents.

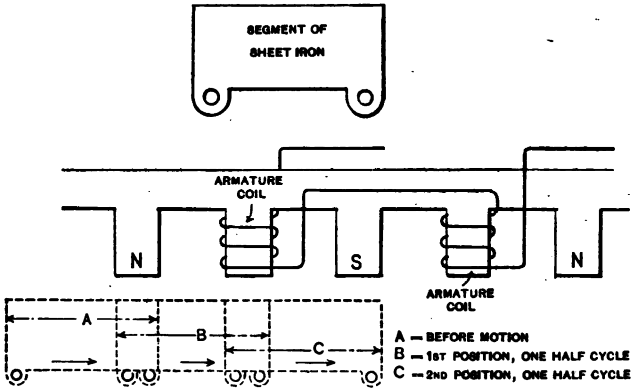


FIG. 162.—The Development of One Cycle by the Motion of a Segment of the Rotor.

Frequency of the Alternations.—An iron rotor which only serves the function of altering the distribution and position of the field lines of force has but one effect upon the frequency. When it rotates fast, the frequency is higher; when it rotates slowly, the frequency is lower. In other words, it is necessary to consider the number of revolutions per second and the number of poles to determine the frequency with which the current alternates per second. Taking any pole as a starting point, the iron segment of the rotor sends lines of force through the armature coil thus affected in a given direction. Further movement of the rotor brings the next segment in such a position that the lines of force pass through the same coil in the opposite direction. A complete alternation has been thereby created, representing 360 degrees. The position of the segment thus means one cycle, when it moves past a N and a S pole, beginning at the N and ending with the S pole, but passing both. Therefore, the total cycles per second are equal to one-half the number of poles projecting radially times the revolutions per second. By this is meant that if there are twelve poles altogether, there are six field and six armature poles. But the six armature poles carry the six armature coils, and each of these coils produces a complete alternation when the rotor segment approaches and when it leaves it. On this basis, an alternator of this type produces as many complete alternations or cycles per revolution as there are armature coils. If there are six armature coils and twenty revolutions per second, there will be 6 × 20 = 120 cycles per second. The point to note in this survey of the subject is that each half-wave or half-cycle is produced simultaneously by each armature coil throughout the system. For instance, the series of segments all move together to send lines of force outward through the armature coils that each respectively covers on the neutral poles. The individual pressures of each coil are added together, as noted before, and the half-cycle is produced at the same instant by each until it is ended. If the segments are now moved forward another step, the same thing occurs, only the lines of force are now reversed in direction in the same armature coils. In other words, the internal action must be regarded as composed of two distinct stages: First, the covering of the neutral poles by rotor segments that are passing before and leaving N poles; second, the covering of neutral poles by rotor segments that are passing before and approaching S poles. Thus, the entire action is summed up in a consideration of the rotor segments leaving poles of one magnetization and approaching poles of another. A revolving iron mass composed of segments is a cheap and simple form of construction. For the generation of alternating currents, the inductor alternator provides one of the best as well as the cheapest types of machines. It is readily perceived that even collector rings are not necessary in this particular type.

CHAPTER XV

DEVELOPMENT OF ELECTROMOTIVE FORCE IN ALTERNATORS. — WAVES WITH A HIGH PEAK. — SINE WAVES WITH A LOW PEAK.—WAVES WITH DISTINCT IRREGULARITIES.—STATION MACHINERY.—ELEMENTS OF POWER AND THEIR EFFICIENCIES.—LIGHT, HEAT, AND POWER DATA.—DEFINITION OF ENERGY.—DEFINITION OF FORCE.—DEFINITION OF WORK.—DEFINITION OF POWER.—DIFFERENCE BETWEEN ELECTRICAL AND MECHANICAL HORSE-POWER. — HORSE-POWER OF AN ENGINE. — THE STEAM TURBINE.—A WATT.—THE KILOWATT HOUR.—FORMULA FOR WATTS.—FORMULA FOR PRESSURE.—FORMULA FOR CURRENT.—FORMULA FOR RESISTANCE.—FORMULA FOR KILOWATTS.—FORMULA FOR HORSE-POWER.—RECAPITULATION.

Development of Electromotive Force in Alternators.—The entire fabric of alternating-current theory is based upon certain assumptions with regard to the electromotive force generated. These assumptions have been variously and collectively understood as fundamentally founded upon a certain rise and fall in the alternating-current wave. That this wave, when so generated, is the legitimate source of all calculations is generally admitted. But departures from what are supposed to exist, and in reality do not and cannot be produced with the apparatus employed, are many. By this is meant that the sine wave, upon which alternating-current theory and practice are dependent, will only be produced in *facsimile* by the electromotive force and current if properly generated. To generate a wave of electricity which corresponds in its form to the sine wave proper, it is necessary to construct and design a field in which these possibilities may be crystallized. The problem, therefore, which appears is one in which adherence to the requirements of theory are absolutely necessary in this respect if a true form of practice is to result; or, in other words, if the generators are going to produce the correct form of current wave. To place this matter in its true light, as one of the most important, in the effort to gain the best possible results in all heat, light, and power problems relating to the application of the alternating current, it is necessary to present a series of cases in which variations occur. These variations are illustrated as cases of where the pressure or potential developed is not of the character expected. It may be high, low, or normal at the moment of generation; and if differing from the normal, it is naturally to be understood that the expressed conditions outlined in theory cannot be in any way met in practice. The reason for comment, therefore, is found in the declaration that the nearer the current approaches a sine wave, the more is it possible to attempt to idealize theory in fact, but the more abnormal the current wave, the more difficult it becomes to attain relatively high efficiencies. The investigations of electromotive force waves may therefore be conducted from the three standpoints: First, how near is the alternating-current wave to its theoretical pattern? Second, in what manner and to what extent do variations occur between the wave dictated by theory and that obtained by practice? Third, what are the results of using a wave which is different in character and value from the one that should have been employed? The entire solution of these three possible conditions means a more intimate knowledge of the governing conditions in a circuit carrying an alternating current. But the governing conditions in practice are those which mould the general problem, and exercise decidedly a limiting effect upon the financial outlay. It may therefore be said with considerable emphasis that the production of a wave of alternating electric energy which does not conform to the strict requirements of theory means the generation, transmission, and distribution of electrical energy in an inefficient form. Or, to put the matter more explicitly, the plant, however well designed, will not represent the degree of returns in the way of power on the one hand, or money on the other hand, unless the sine wave is duplicated as far as possible. The sine wave is therefore the best means of getting a presumably high efficiency in practice, provided the apparatus, including the generators, transformers, etc., is correctly and therefore efficiently designed. The point thus advanced, that the sine wave must not be too high and peaked, neither must it be too low and broad, is well worth careful consideration. The deliberate production of a wave that in any way complies with certain extraordinary conditions is thus a different matter, and it may be stated without reservation that such cases actually exist. One instance that may be recorded is that in which what is commonly called vacuum-tube lighting is being done. In this case the wave is generated with a certain extended form, differing from any type of wave in use. The power employed is alternating, and it is stepped up or raised to a very high value for use in creating intense molecular bombardment through tubes of glass more than 50 feet in length. This form of lighting is referred to for the reason that it partakes of certain characteristics that may eventually lead to its more widespread use than at present. The alternating-current waves referred to, however, are of a form which makes an interesting study, particularly in relation to the generator and the rest of the equipment of a power plant.

Waves with a High Peak.—What is meant by waves with a high peak is that form or type of waves in which the electromotive force rises very rapidly (Fig. 163) to a high value. The pole piece, it must be understood, is therefore shaped in a certain manner. A conductor, moving in the ordinary manner under the ordinary pole piece, will, no matter how quickly or how slowly it is moved, produce relatively the same type of wave. Moving conductors slowly or quickly will not produce the high altitude or peak in the sine wave. The only way in which such accentuation results is from the use of pole pieces which have a very intense field at their median line. By this is meant that a pole piece with

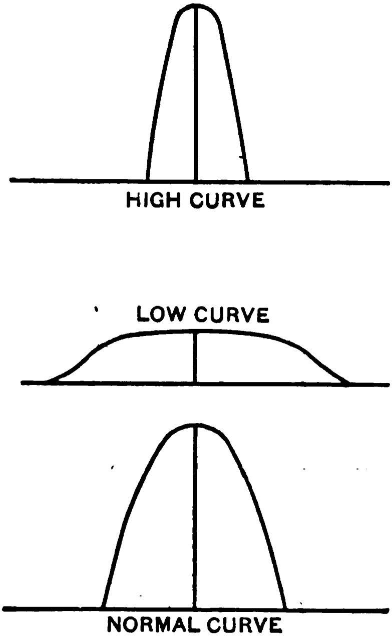


FIG. 163.—Types of Waves.

a comparatively weak but graduated field from the tips to within a short distance of the center will tend to produce a peaked sine wave in a moving conductor. The illustrations (Fig. 164) show the manner in which this idea may be and is developed

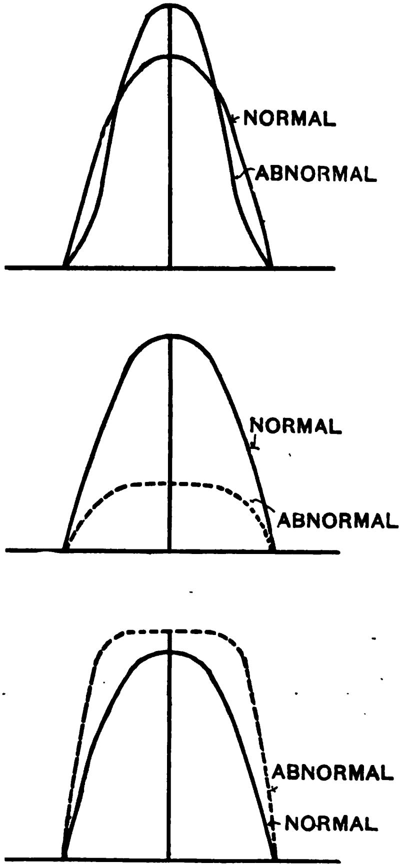


FIG. 164.—Comparison of Superposed Normal and Abnormal Waves.

in the design of alternator pole pieces, intentionally or not, as the case may be.

Sine Waves with a Low Peak.—There is such a thing as a wave with a low peak. A low peak, or a broad and rather flat wave, is due to ordinary conditions such as are generally found in the pole piece. It is perhaps an easier matter to produce a flat wave than a high, sharp wave of pressure. The beginning of every electromotive force wave is found at that point far enough away from the pole tip to just begin to provide "magnetic fringe," as it is called. The fringe extends beyond the pole tip a certain distance on each side. The fringes of adjacent poles may or may not meet. Should they meet, then the electromotive force begins in an opposite direction to that which just ended, due to the conductor passing the last pole. The idea, therefore, is to discover whether the pole fringe extends very far on each side. The next point to discover is whether the pole piece is producing a very uniform or an irregular mass of lines of force. The more irregular the distribution of the lines of force, the more irregular (Fig. 165) will be the shape of the curve resulting from any graphic plotting process. It may be readily understood, in speaking of irregular grouping of the lines of force, that this irregularity may be due to other influences than those of design. The shape of the pole piece is only one of the controlling influences; there is still to be considered the condition of the metal composing it. Hard patches may be the means of lowering the permeability of the iron wherever they exist. That they may be found in castings is only too well known. For this reason

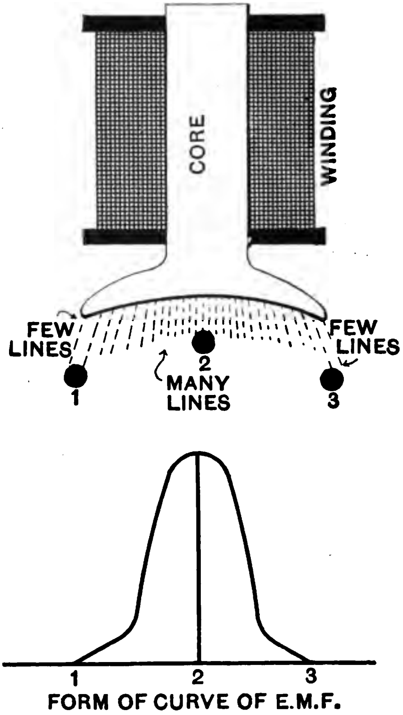


FIG. 165.—Pole Piece and Corresponding Wave.

a machine finished as it was originally designed, with the design correct, may produce an electromotive force curve of a most irregular character. The iron must be carefully considered in all tests relating to the shape of the curve. This being so, it is not difficult to realize how easily a sine wave may be transformed (Fig. 166) from what it was originally intended to be to an entirely different product. The fringe near the pole edges, which are cut by the moving conductors, may only extend a short distance away; in which case the conductors (Fig. 167) rapidly enter the full field, which varies

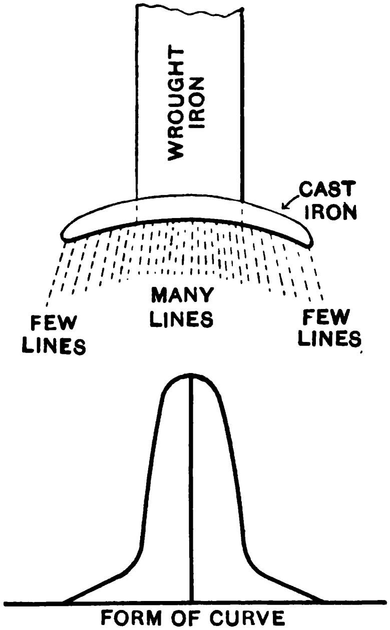


FIG. 166.—Sudden Rise of Pressure Noted.

very little in strength. The result of this is naturally the development of a comparatively uniform electromotive force. The shape of the pole pieces, as claimed, particularly the pole tips, is the means employed for moulding the electromotive force wave to any shape within reason desired. A pole piece may have blocks of metal set into it if necessary. These blocks may be of a permeability so selected that the wave is peaked (Fig. 168) whenever desired. In direct-current design the main cores are frequently surrounded with a pole plate of an entirely different permeability (Fig. 169) from the iron. This practice does not exist in alternating-current design; but when used in direct-current

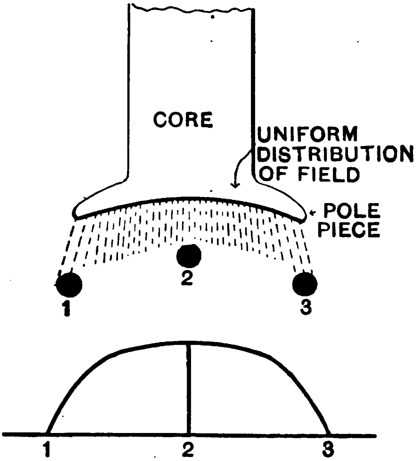


FIG. 167.—Development of a Flat Wave.

generator construction, it is for the purpose of getting a certain distribution of the lines of force otherwise impossible. For instance, a wrought-iron core, developing a magnetic field of 100,000 lines of force per square inch, represents a case in which the lines of force must be sent through an air gap. To attempt to secure magneto-motive force, or ampere turns, sufficient to do this is not practical. The only way to secure a reasonable number of ampere turns

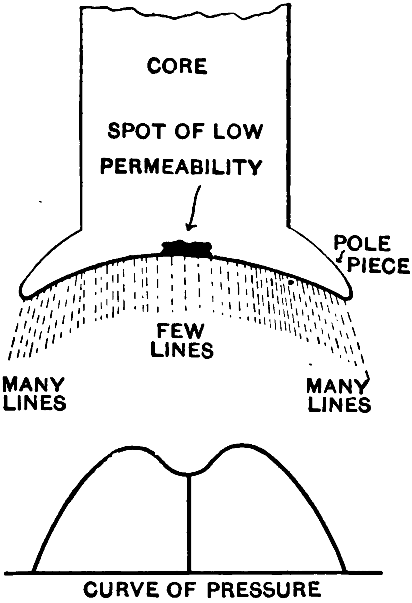


FIG. 163.—Effect of a Bad Distribution Due to a Blemish.

is to secure a reasonable field in the air gap. For this reason the lines of force, as they pass from the core into the air gap and armature core, are amply distributed by means of an attached pole rim of steel or cast iron. The alternator, as far as it has been considered with regard to its pole-face distribution, appears in common with the direct-current generator as a machine whose field can be designed with due reference to its obvious function, that of generating an approximate sine wave.

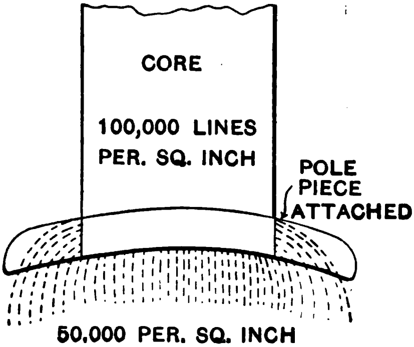


FIG. 169.—Lines of Force Distributed Uniformly by an Attached Pole Piece.

Waves with Distinct Irregularities.—Irregularities in the wave form are frequently the cause of damages to insulation, as well as a general lowering in certain specific instances of the total efficiency. The net result of peaks in the waves is in some cases almost as bad as that of the opening of the circuit. There are severe cases of self-inductive action only attributable to wave variations as illustrated. The pole may be so designed that its pole tip extends farther on one side than on the other. In this case

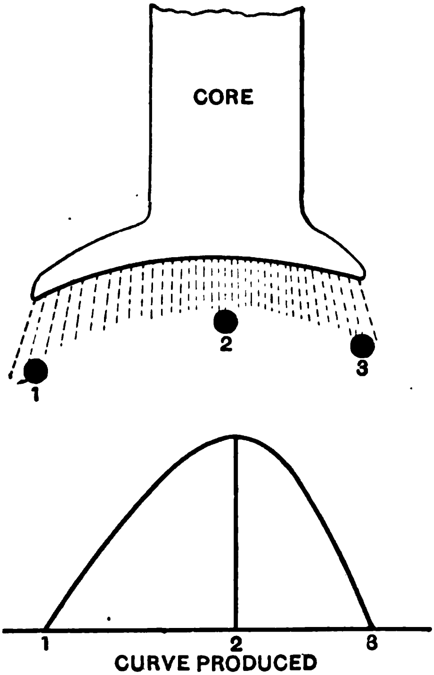


FIG. 170.—Effect of Bad Pole Tips on E.M.F.

the wave of pressure would rise on one side much more suddenly (Fig. 170) than on the other. A series of conductors passing a variety of pole pieces would, under such conditions, produce waves which introduce injurious reactions. Two-phase and three-phase machines are just as likely to possess this defect as single phase. When it is remembered that in a single-phase machine the E.M.F. of waves of one direction is all in series, and the E.M.F. of waves of the opposite direction likewise, it becomes evident that, conductors passing two irregular north poles for instance, producing waves of such a character respectively that the first rises slowly, but the second rapidly, then the second develops more reactance and possibly other faults which disturb the normal and expected conditions. The idea, therefore, is to obviate as far as possible waves possessing more than one peak, or even a tendency to more than one. The design of pole pieces is thus an important matter in connection with the generation of sine waves. It is not to be believed, however, that all alternators are necessarily useless because they do not produce exactly the wave expected. But it is to be believed that alternators producing waves which differ to a marked degree from the ordinarily accepted standard will fail through their inability to comply with the relationships that must exist between electromotive force, current, and the angle of lag as calculated for regular practice.

Station Machinery.—In order to distinguish between the various types of plants in service, it is necessary to examine into their functions in this wise: Whether they supply electricity under the rights granted by a franchise; or whether their field is more circumscribed in this sense, though not necessarily more limited as far as the number of kilowatts generated and distributed is concerned. The point to be considered in connection with direct- and alternating-current machinery is its application to a commercial purpose. Whether the motors or generators are of the direct- or alternating-current type, they must represent a reasonable cost with respect to their capacity, have a reasonable efficiency with respect to their output, and be of a reasonable size both as regards floor space and bulk. There are two elements to consider in the case: First, the point from which power is sent over the line (Fig. 171); second, the point or points at which it is received (Fig. 172). The installation of machinery is therefore dependent, as far as its character is concerned, upon the purpose to which it is to be applied, the distance over which power is to be sent, the efficiency at which it is to be delivered, and the climatic conditions or other meteorological peculiarities that will affect the installation as a whole. The use of a very high instead of a very low pressure is entirely dependent upon commercial requirements, the most important of which is the necessity of securing a profit on the sale of current, a thing impossible if there is too great a waste in the lines carrying it to its point of sale. In other words, the care and attention given to the details of a plant are as much a matter of business importance as they seem to be of a technical or purely scientific importance. The situation that presents itself is that of

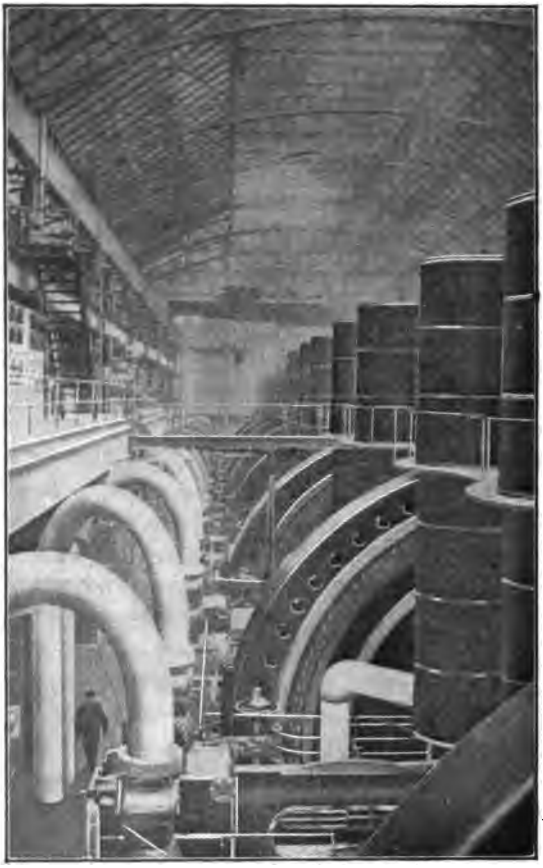


FIG. 171.—Manhattan Power Station, N. Y.

a series of discounts demanded at various points in the process before the consumer is reached. Beginning with the generation of the current, the coal, water power, or gas is the first item to consider.

Elements of Power and Their Efficiencies.—With respect to the discount idea, a high-efficiency machine means paying less for power than does one of lower efficiency, provided there is not too great a disparity in cost in favor of the lower efficiency. In other words, as it is evident that beyond a certain point efficiency in a machine becomes very expensive, a difference of a few per cent. might mean a great difference in first cost, and therefore not the financial advantage anticipated. A list may be drawn up of the efficiencies to be met with and secured in actual practice, including all the essential elements of a plant, such as may be classified according to their purpose:

Generating Section..	Coal, Water Power, Gas. Boiler, Steam Engine, Gas Engine, Turbine. Generator.
Transmitting Section	Switchboard. Transformer. Lines.
Distributing Section.	Transformers. Rotary Converters. Feeders, Consumers' Circuits.

The detailed efficiencies will have to be considered in groups, beginning with the original source of power in each instance. In the various cases shown in practice there appear steam, gas, and water

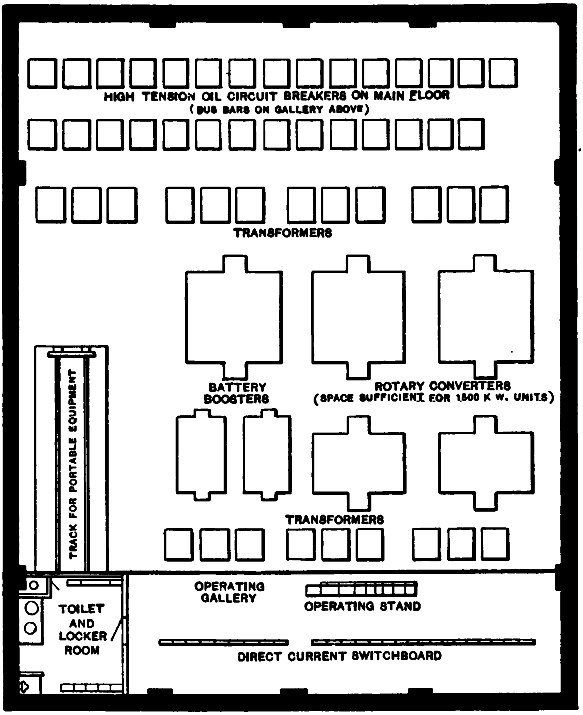

HIGH TENSION OIL CIRCUIT BREAKERS ON MAIN FLOOR
(BUS BARS ON GALLERY ABOVE)
TRANSFORMERS
BATTERY BOOSTERS
ROTARY CONVERTERS
(SPACE SUFFICIENT FOR 1500 K W. UNITS)
TRACK FOR PORTABLE EQUIPMENT
TRANSFORMERS
TOILET AND LOCKER ROOM
OPERATING GALLERY
OPERATING STAND
DIRECT CURRENT SWITCHBOARD

FIG. 172.—Plan of the Operating Elements of a Modern Sub-Station or Distributing Section.

power in ordinary use. A steam plant includes the coal boiler, engine or turbine, generator, switchboard, and outgoing currents or lines. A gas plant excludes the boiler, and consists of the coal or fuel, gas-producer plant, gas engine, generator, switchboard, and outgoing circuits or lines. A water-power plant consists of the kinetic energy of the water, the water turbine or wheel, the generator, switchboard, and outgoing circuits or lines. A comparison of the three may be made as follows:

ELEMENTS OF A POWER PLANT.

Steam-power plant.	Coal or oil.	Boiler.	Engine or turbine.	Generator.	Switchboard.	Lines.
Gas-power plant.	Fuel.	Gas producer.	Gas engine.	Generator.	Switchboard.	Lines.
Water-power plant.	Water power.		Turbine or wheel.	Generator.	Switchboard.	Lines.

The power element in each case may be regarded as unity, or 100, and the estimates of efficiency made from that point. Taking the coal or oil and water power in the various plants as having 100 units of power, the efficiencies would follow along these general lines:

	STEAM.		GAS.		WATER.	
1.	Coal or oil	100	Fuel	100	Water power	100
2.	Boiler	30 to 70	Gas producer	*	Turbine or wheel	80
3.	Engine or turbine	14	Gas engine	14	Generator	90
4.	Generator	90	Generator	90	Switchboard	98
5.	Switchboard	98	Switchboard	98	Lines	90
6.	Lines	90	Lines	90		

In the three columns of figures the individual efficiencies have been accurately noted, with the exception of the boiler and gas producer. The reason for this is as follows: The fuel consumed by the boiler in comparison with that of the gas producer is more than twice as great for an equal quantity of power produced by both steam and gas engines. In other words, the number of pounds of fuel productive of 100 hp. hours is greater with a steam- than with a gas-plant equipment. Beginning with the fuel, in both the steam and the gas plant, the items are alike in number, the boiler and gas producer being entirely different types of power extractors, if such a term is admissible. In the boiler the heat units are absorbed by the water, and, as expansive energy, are ready to develop systematic power. In the gas producer the fuel is distilled, and the gases are ready, when mixed with a proper quota of air, to produce, by explosive force, the necessary and expected power. The water-power plant needs little comment, except in so far as the high efficiencies are seen to be sustained throughout the system. To realize what a table of this kind means, take the first column of figures, that of the steam plant. The boiler may vary from 30 to 70 per cent., depending upon the amount of heat it absorbs. In this case, averaging up the boiler at 60 per cent., the engine efficiency means 14 per cent. of 60 per cent., or 8.4 per cent. The generator at 90 per cent. gives a return of 7.56 per cent., and the switchboard and lines a return of about 7 per cent.

When 100 pounds of coal are burned in the boiler, on this basis, a return equivalent to the heat value of 7 pounds is recovered. The return is greater or less according to the boiler efficiency, though it is evident that, even at its highest, the engine is bound to pull the efficiency down. Exploding the fuel products, instead of utilizing the heat directly, gives a higher efficiency with a gas system; and the case of the gas producer, instead of the boiler, is considered a distinct advantage.

Light, Heat, and Power Data.—A few definitions and tables may prove useful in cases where judgment would otherwise be at fault. The distinction to be made between energy, force, work, and power is one of the instances to which attention is drawn.

Definition of Energy.—Energy is the capacity to do work as ordinarily defined. There are two kinds: Kinetic, or energy of motion; and potential, or the energy of position.

Definition of Force.—Force is that which moves, or tends to move, matter. If applied over a given distance, so that perceptible results are visible, it is characteristically named, but only because of the new circumstances of its appearance.

Definition of Work.—Work is the product of force and distance. When energy is spent or transformed, or when force is applied to overcome a resistance, work is done.

Definition of Power.—Power is the rate at which work is being done. The terms watt, horse-power, and kilowatt are simply evaluations of a given amount of work done in a given time. The amount of work done has nothing to do with the rate at which the force is applied. A horse-power, for instance, is simply an expression given to a certain volume of work in a given time. Mechanical and electrical power are identical, except that one is rated a little differently from the other.

Difference Between Electrical and Mechanical Horse-power. — An electrical horse-power equals 746 watts per second. A mechanical horse-power equals 33,000 foot lbs. per minute. According to this, $\frac{1}{60}$ of 33,000 foot lbs. equals 746 watts per second, or 550 foot lbs. per second equals the rate expressed by 746 watts during the same period of time.

Horse-power of an Engine.—The mean steam pressure on the piston multiplied by the distance in feet the piston moves in one minute gives the number of foot pounds developed by the steam and engine per minute. It is essentially no different from the lifting and lowering of a weight to do work, except that the steam pressure when in action is like a force that is used in two ways: expansively and by sheer impact.

The Steam Turbine.—The impact idea is utilized in the steam turbine to revolve a wheel with little buckets arranged around its periphery. The steam strikes the buckets, rotates the wheel, and develops foot pounds over a distance equal to the blow multiplied by the feet of distance it travels, namely, the circumference of the wheel. Some expansion is obtained, but the steam largely acts as a series of infinitesimal projectiles, each delivering a certain blow, and thus in sum total developing visible rotation. The steam-engine formula is PLAN divided by 33,000, and can be easily remembered as such; P being the average pressure, L the length of stroke in feet, A the area of the piston in square inches, and N the number of strokes per minute. In the steam turbine, the feet equal the circumference of the disk; the pressure of the steam and the impact are averaged up by reference to special formulas. The bucket gives the area in square inches, and the revolutions the speed. For instance, a peripheral torque of 100 lbs., on a disk of 3 feet, would mean about 10 feet circumferentially, or 10 × 100, equal to 1,000 foot lbs. per revolution. At 1,000 revolutions per minute, the foot lbs. equal 1,000 × 1,000 ft. = 1,000,000 foot lbs. total, or, dividing by 33,000, about 33.333 hp.

A Watt.—When amperes are multiplied by volts, the product in watts forms the basis of electric-power calculations, or electric power = electrical work ÷ time, or

$$\begin{aligned}\text{Watts} &= \frac{\text{work}}{\text{time}} \\ &= \frac{\text{volts} \times \text{amperes} \times \text{seconds}}{\text{seconds}} \\ &= \text{volts} \times \text{amperes}.\end{aligned}$$

According to the estimates of a mechanical and an electrical horse-power, 746 watts = 550 foot lbs. per second; on this basis, 550 foot lbs. ÷ 746 watts = .7375 foot lbs. per second; or 1 foot lb. = 1.356 watts per second.

The Kilowatt Hour.—Multiplying the kilowatts by the hours gives what are called kilowatt hours. A 10-K.W. generator, feeding a circuit for 10 hours, has supplied 10 × 10 = 100 K.W. hours; or a certain number of watts, for a certain number of hours, grouped into lots of 1,000 for the time specified. For instance, 2,200 watts for 5 hours means 5 × 2,200 = 11,000 watt hours, or 11,000 ÷ 1,000 = 11 K.W. hours. Combinations of power and time are frequently employed in order to gain a better conception of the volume of work done; in such a case, for instance, as the motor or lighting load of a central station.

Formula for Watts.—The following grouping may prove convenient in making calculations for watts:

$$\text{Watts} = E \times C$$

$$\text{Watts} = C^2 \times R$$

$$\text{Watts} = \frac{E^2}{R}$$

Formula for Pressure.—The following formula may prove convenient in making calculations for volts, where R equals resistance and W watts:

$$\text{Volts} = \frac{W}{C}$$

$$\text{Volts} = \sqrt{W \times R} = \frac{\text{Hp.} \times 746}{C}$$

$$\text{Volts} = C \times R$$

Formula for Current.—The following formulas may prove convenient in making calculations for amperes:

$$C = \frac{E}{R}$$

$$C = \frac{W}{E} = \frac{Hp. \times 746}{E}$$

$$C = \sqrt{\frac{W}{R}}$$

Formula for Resistance.—The following formula may prove convenient in making calculations for ohms:

$$R = \frac{E}{C}$$

$$R = \frac{E^2}{W} = \frac{E^2}{Hp. \times 746}$$

$$R = \frac{W}{C^2}$$

Formula for Kilowatts.—These formulas give the number of kilowatts as indicated:

$$\text{Kilowatts} = \frac{C \times E}{1{,}000} = \frac{C^2 \times R}{1{,}000} = \frac{E^2}{1{,}000 \times R}$$

Formulas for Horse-power. — The horse-power formulas along electrical lines are as follows:

$$\text{Horse-power} = \frac{E \times C}{746} = \frac{C^2 \times R}{746} = \frac{\frac{E^2}{R}}{746} = \frac{E^2}{746 \times R}$$

Recapitulation.—The brief outlines given of the principles underlying the development of certain light, heat, and power problems are readily understood as being essentially the outlines of modern practice, though much simplified and abbreviated. The part alternating currents have played and are now playing in the development of certain economic problems which the promoters and extenders of lighting and power enterprises contend with, may be defined to such an extent, that the application of the alternating current in daily practice, will become more emphasized than ever, and thus eliminate even the problematic side it is still supposed to bear in certain instances. As has been frequently stated by others, and is now better understood than ever, the art of economical applications is of the same importance in electrical propositions as fundamental principles are in commercial houses. In fact, engineering is largely a profit-and-loss scheme, with a predominance in favor of the profit, and a constant effort to reduce the loss, with the difference that the ways and means, the intervening mechanism in fact, is somewhat newer. Commercial systems are as old as the real beginnings of business life. Engineering systems which produce light and power, on the contrary, are relatively recent. The study of the means of shaping the mechanism to accomplish the same purpose as that of the merchant is thus the *finale* to the scientist's or engineer's work. But as long as human ingenuity persists, just so long will there be constant changes in the systems of lighting and power, or any other form of engineering or inventing that is necessary to the further development of personal comfort and security or industrial expansion. The interest now taken in engineering projects is no longer local, but national. The discovery, as the result of a somewhat retarded educative process, that electricity is in a great variety of ways the real solution of what were once considered impossible conditions, has made it, in all probability, the national panacea for many ills. Among those ills were the limitations of city expansion without adequate means of getting from work to home. The lighting of thoroughfares was another problem, and the obtaining of cheap power and the utilization of distant sources of power still another. But though they may all be listed and referred to in this manner, the fact of the matter is they have dropped out of sight because of the ease with which the remedy proved effective. At present the student of electrical progress, whether technically or scientifically equipped, will be much better able to form an intelligent opinion of the stages of expansion by a general than by a limited view of the field. What alternating currents have accomplished is but the second chapter of that volume of the future still unwritten. Practice is bound to change, and in that change the direct and the alternating current will be better understood, at least so far as their relative importance and perpetuity are concerned.

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